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JUNE 2025

SANT'AGATA SYMPHONY

Lamborghini blends hybrid and high RPM

iVT EXPO
Powertrain highlights from the off-highway show in Cologne p50

IMMERSION EXPERIENCE
Dive into the ultimate approach to battery cooling

McLAREN W1
All-new MHP-8 in the spotlight

HEAVY HYDROGEN
JCB's H_2 ICE technology investigated

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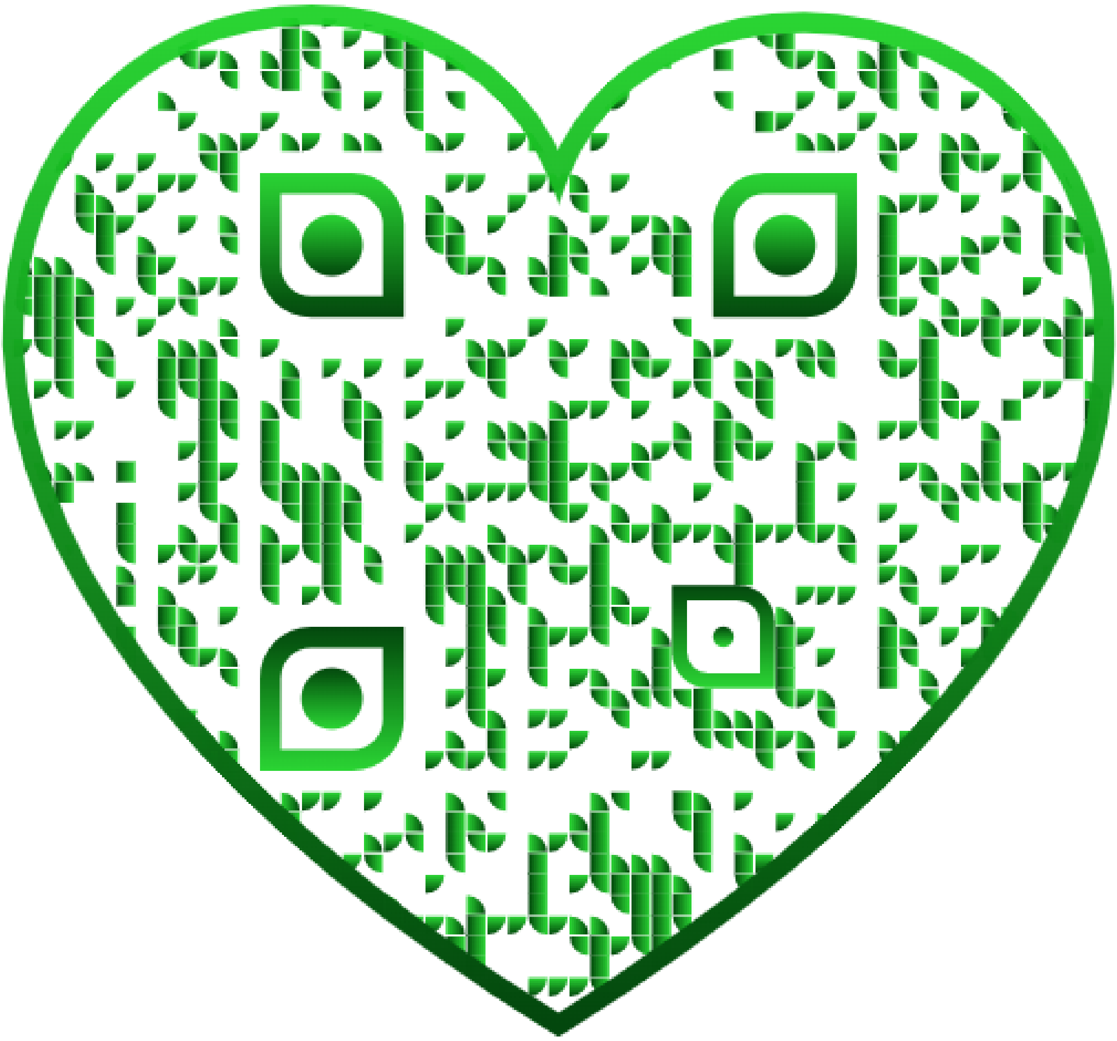

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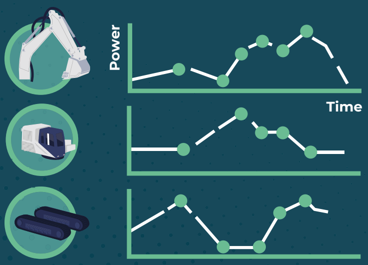

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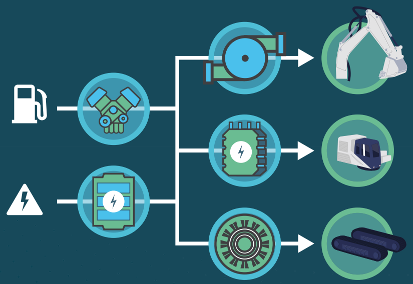

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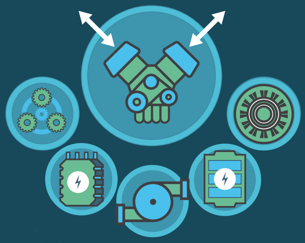
Cost, Mass and Volume Comparison



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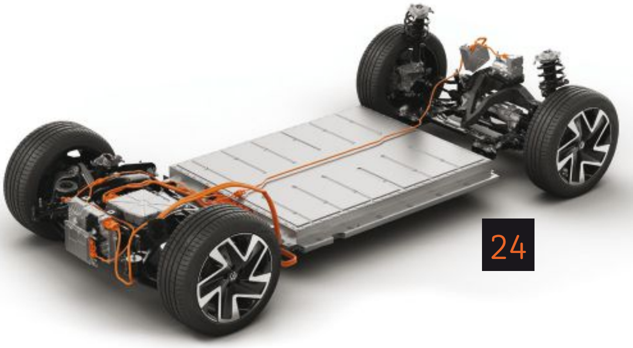
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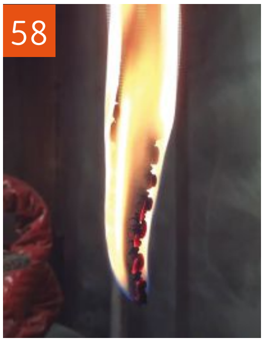
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Editor's note

The automotive old guard is struggling. Some of the causes are out of their hands, driven by political agendas, but others are of their own making. Talking to various industry figures in recent months, I've realized that one of the biggest challenges facing what we shall call incumbent manufacturers is the sheer rate of change. Twenty years ago, if you could bring an all-new car to market in five years you were doing well.

That simply won't cut the mustard these days. BYD has a product development cycle of around 18 months. At the end of 2023, VW expressed a desire to trim its new product development cycle from 54 to 36 months, starting with the ID.2. At the time, this was comparable to BYD; unfortunately for VW, its Chinese competitors are just getting faster.

There is a conversation to be had around the price competitiveness of new market entrants, but what should be far more worrisome to existing manufacturers are the legacy structures and practices that are keeping them slow. Once, European OEMs could rely on their products having a quality edge, but the latest offerings from BYD, Omoda and others have closed the gap, and every year they just get better.

If the established giants are to compete against companies with phenomenal R&D resources (BYD has more than 100,000 engineers), more horizontal structures and less bureaucratic inertia, they need a fresh approach, fast. For example, although software might not fix your company structure, solutions such as those detailed in the ZeBeyond supplier interview on page 48 are being developed to narrow down development choices for powertrain, chassis and so on, much more rapidly. As one source noted, everyone wants a 3D model of everything, when in reality that is overkill during the early stages of a project.

Mindsets need to change at a corporate level too. Multiple rigid layers of management do not lend themselves to nurturing innovative and agile thinking. Of course, standards need to be maintained, but engineers across the board should be given freedom to push forward new ideas without becoming mired in internal company politics and endless rounds of approval.

Europe's automotive industry could be about to squander over a century of accumulated expertise and innovation. The next few years will be decisive: it must adapt or die.

Lawrence Butcher

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- *ENERGY EFFICIENCY*
- *POWERTRAIN OPTIMIZATION*
- *THERMAL MANAGEMENT*

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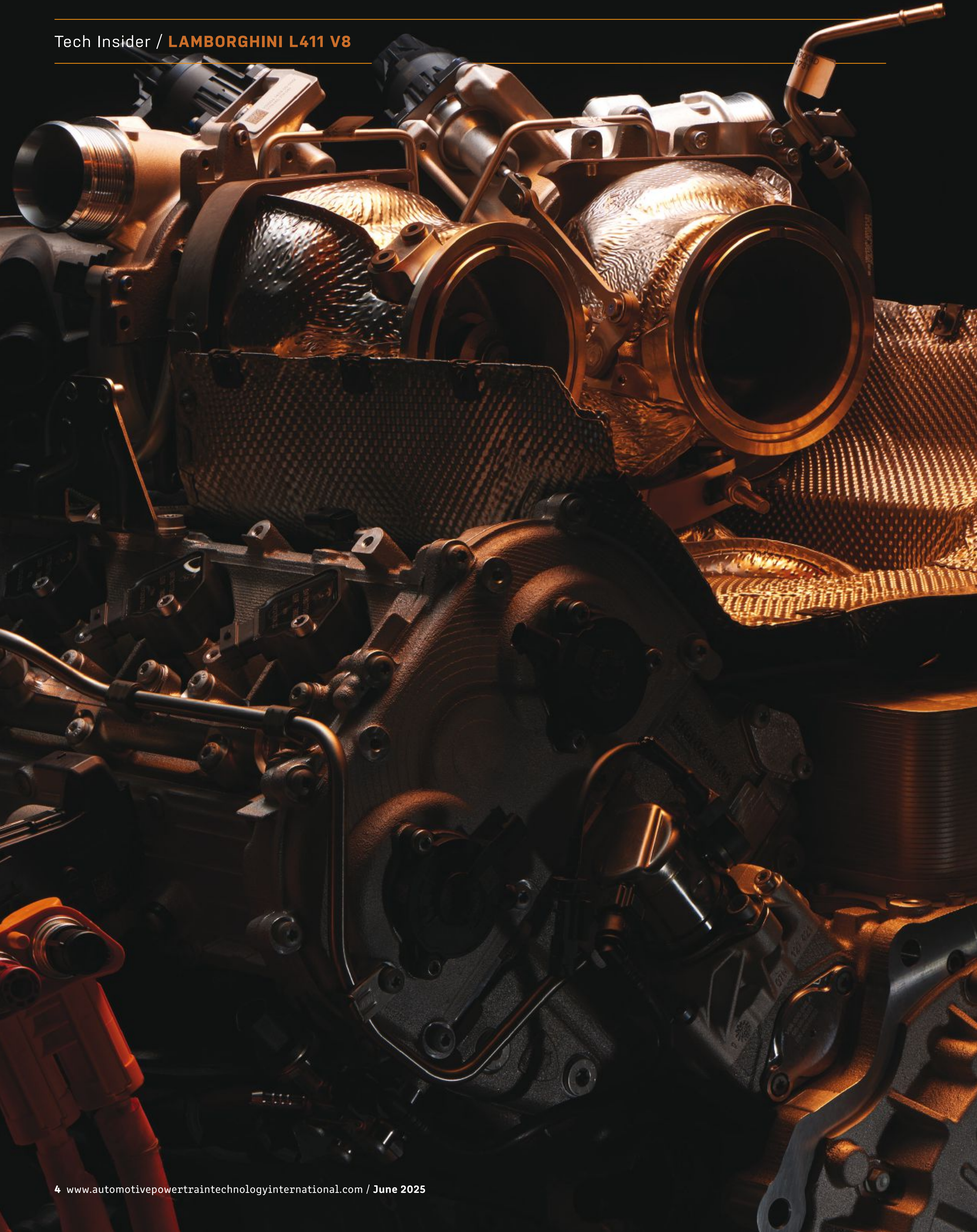
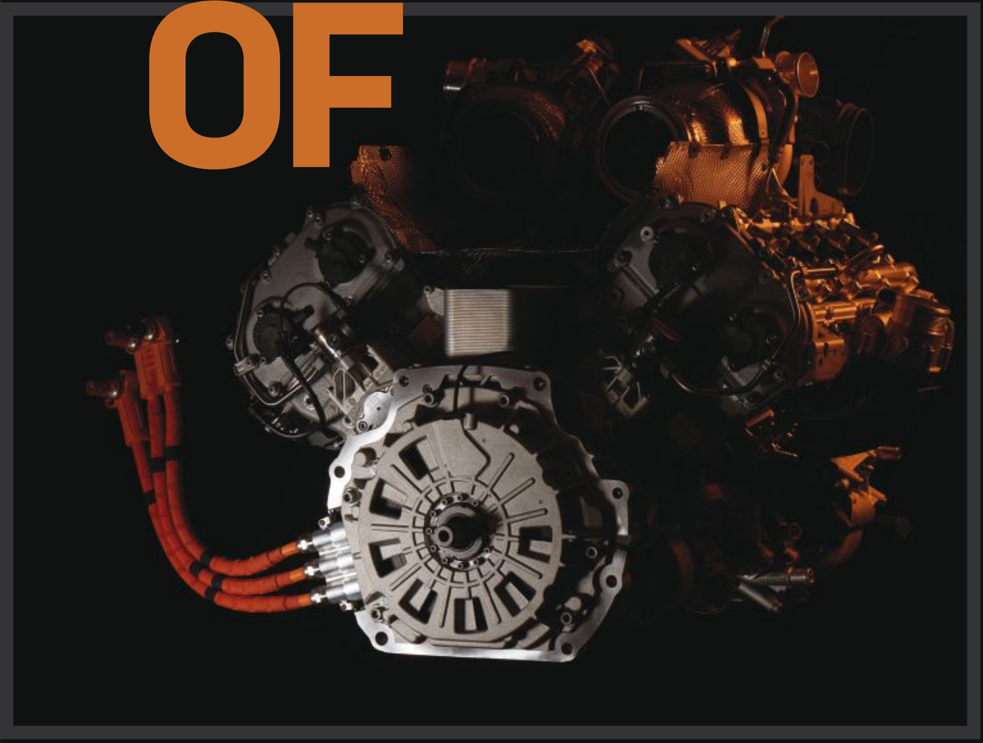


APEX OF INNOVATION

HOW DOES A MANUFACTURER RENOWNED FOR CARS THAT ASSAULT THE SENSES HANDLE AN ERA OF LEGISLATION INTENDED TO MUTE SUCH EXHIBITIONISM? BY CREATING A HYBRIDIZED V8 THAT SOUNDS AND FEELS LIKE A RACE-BRED NA MOTOR

Words: Lawrence Butcher



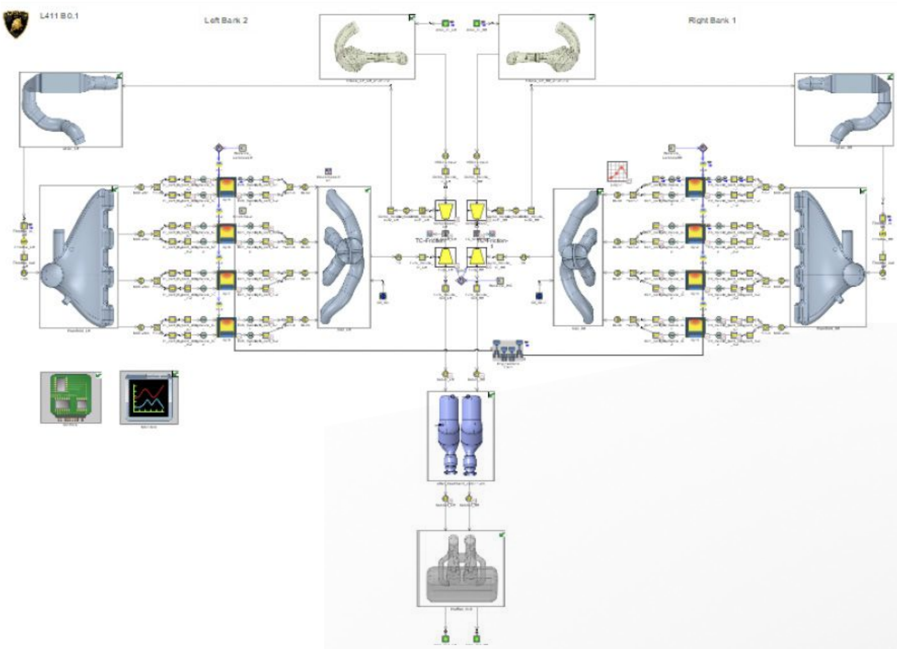


FIGURE 1. 1D ENGINE PERFORMANCE MODEL

> "It is becoming quite challenging to do a fun engine that is still compliant with emissions. Hybridization gives us tools that 10 years ago we didn't have"
>
> **Alberto Santucci, Lamborghini**

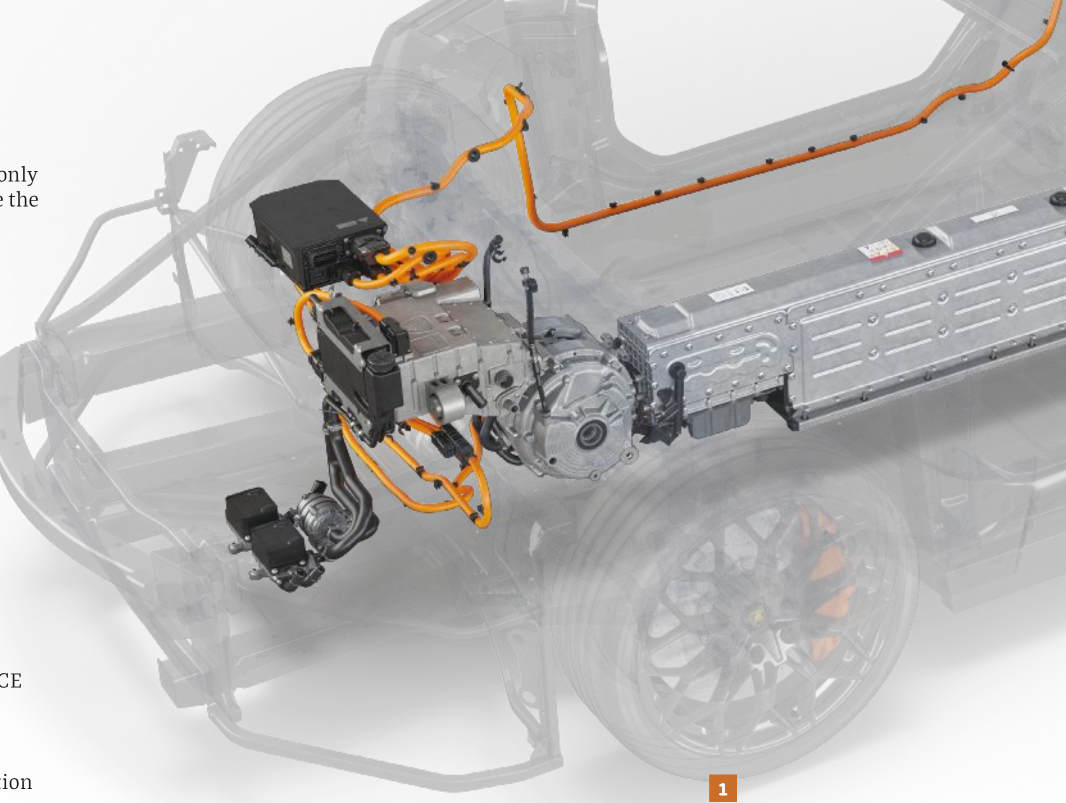
Until recently, Lamborghini had only made five all-new engines since the 350 GT was launched in 1963: three generations of V12 (the original of which stuck around for nearly 50 years), a V10 (which Audi later adopted) and a V8 designed in the 1970s by Gianpaolo Dallara – ignoring the Audi-sourced V8 found in the Urus. So the L411 – which debuted in the Temerario in 2024 – is a big deal, if not the most significant engine since the Sant'Agata marque's first.

The headline figures are impressive. The four-liter, twin-turbo V8 revs to 10,000rpm, delivering 800ps, with a combined output, including the hybrid system, of over 920ps. However, these figures only scratch the surface. What makes the L411 truly impressive is its development from the outset as a full hybrid powertrain, with a level of integration between ICE and electric not seen before.

THE BRIEF

The task facing Lamborghini head of vehicle motion Davide Bizzarri and his team was a momentous one: replacing the visceral, emotive, naturally aspirated V10 of the Huracán with a turbocharged unit that futureproofed the powertrain against emissions regulations, without losing the analog spirit that owners crave. Among the supercar manufacturers, Lamborghini has always won the Top Trumps battle on road presence, so a low-revving, muted turbo-eight was never going to make the grade. "We wanted to get the best of both worlds: the torque of a turbocharged engine, integrating an e-machine, but also an engine that revved to 10,000rpm to keep that DNA," says Bizzarri.

To achieve this, Lamborghini needed a clean-sheet design. From the outset, the L411 was designed to be hybridized, from both a structural and a combustion perspective. A P1 hybrid layout was selected, but the axial flux motor (supplied by Yasa) is not simply sandwiched between the engine and transmission – it is fully integrated into the crankcase, enabling it to fit within the available packaging space of the Temerario, Lamborghini's Huracán replacement.



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1. HYBRID COMPLEXITY
The L411 V8 is matched to a pair of axial flux motors on the front axle and a battery mounted along the central spine of the car

ARCHITECTURE CHOICES

The L411 is a 90°, all-aluminum V8 with dual overhead camshafts on each cylinder bank actuating four valves per cylinder. It is an over-square design, using a 90mm bore and 78.5mm stroke, with a flat-plane crankshaft. A hot vee configuration was settled on, determined by early simulation work and the space available in the engine bay. The turbochargers are sized to support efficient, full-power operation at high speed, enabled by the hybrid motor providing torque infill at lower RPM. Mechanically, the engine is built to sustain very high RPM operation.

However, the choice to use a flat-plane crank came with downsides, not least balancing. One option was to use counter-rotating balance shafts, but this was dismissed due to the added weight. Instead, a torsional vibration damper (Figure 4) was developed. In combination with a piston-to-bore ratio optimized to minimize piston weight while ensuring sufficient bore diameter to support high-speed combustion, plus titanium conrods and high-strength, long-term gas-nitrided steel for the crankshaft, this provides sufficient robustness for the reciprocating components. Of course, the valvetrain also needed special attention, which will be covered in detail later.

THE PERFECT COMPROMISE

As Alberto Santucci, emissions and OBD technical coordinator at Lamborghini, explains, a new approach was needed to create a V8 that kept its soul while meeting ever-tighter regulatory constraints. “It is becoming quite challenging to do a fun engine that is still compliant with emissions,” he says. “Technology is helping us a lot. We have some additional degrees of freedom, and hybridization gives us tools that 10 years ago we didn’t have.” The solution required merging what until recently has been considered race engine technology with a combustion and hybrid concept to hit those demanding emissions targets.

There is enormous complexity in the interactions between the various engine (and hybrid) parameters, so close collaboration between the various specialized teams was essential to bring it all together. “You need to lay the foundations right, and we worked very closely with our colleagues during the design concept phase,” says Santucci. “That helped guide the decision process: picking the right injector, picking the level of turbulence that we want in the combustion chamber or the combustion chamber design itself, working on the catalyst design. Those fundamental jobs must happen way before an engine is running. To achieve the targets

LAMBORGHINI HAS CONDENSED ALL ITS POWERTRAIN CONTROL INTO A SINGLE UNIT

CONTROL FREAKS

Harmonizing the various elements of the Temerario powertrain, from the front motors through the battery to the ICE and P1 hybrid, is a complex task. Impressively, the entire process is handled by a single control unit.

“The engine control unit, in terms of software, is also coordinating both the current split on the different e-machines and battery,” explains Alberto Santucci. “We’re receiving the current limit from the BMS, and then it is the engine control unit that allocates the different levels of current to the different inverters. And we do the same for the torque. Once we know the limit of the different e-machines, we can then distribute the torque accordingly to our strategy. This high level of hybridization means you can do a lot with strategy, and that is all controlled within the ECU.”

The ICE is treated as two individual four-cylinder engines, with the main ECU effectively incorporating two separate controllers. “This was the right thing to do, because the two banks are not always the same and you want to have independent boost control over each bank – they are not joined by a balance pipe,” says Davide Bizzarri.

There is a separate processing unit dedicated to ignition control, which also encompasses the knock detection system. Rather than using acoustic knock detection, Lamborghini has harnessed a process known as ion sensing.

This measures the current of the ionization within the combustion chamber, which can be processed to show the combustion chamber pressure on a cycle-by-cycle basis. The system also enables the fuel octane to be automatically detected, meaning the ignition can be retarded if low-quality fuel is used.

required a total team effort to get the foundations right and ensure the engine can achieve the emissions we need."

The intake ports and combustion chambers were honed to provide high tumble flow to encourage fast combustion and homogeneous mixture distribution. Using a combination of three-dimensional CFD and 1D simulations (Figure 1), the gas exchange concept and related valve lift profiles were developed to optimize three key areas: minimizing scavenging at lower RPMs to help with emissions, achieving lambda close to 1 in the mid-RPM operating range, and minimizing backpressure and EGR at high RPM to ensure stable combustion.

"We studied many geometrical configurations [for the inlet] in order to evaluate the parameter known as omega tumble," notes Giovanni Bonandrini, CAE engineer at Lamborghini. "This is a motion inside the cylinder that is not useful for the combustion and creates high flow velocity close to the plug. You run the risk of having a combustion system that has high turbulence levels, good mixture formation, but very high speed close to the spark plug." The result of this would be considerable combustion variability at high speed and full power, so a compromise had to be found with high enough – but controlled – omega tumble.

Following the DOE process, two intake geometries were selected for further investigation, one with medium tumble, another with high tumble. Though the medium-tumble design gave higher turbulence near the plug, the mean tumble values across the cylinder were greater with the high-tumble design. Various DOEs were also run, looking at aspects such as intake and exhaust camshaft phasing, injection and timing strategies to arrive at a solution that met Lamborghini's targets. Given the 10,000rpm goal, it was decided that variable lift systems for the valves were not viable.

VALVETRAIN DEVELOPMENT

The valvetrain design is a first for a true production engine because it uses sliding finger followers to actuate the valves directly. The follower/valve interface was subjected to extensive modeling and simulation work to find a way to make the system as reliable as possible. The camshaft lobe-follower kinematics were optimized to limit contact pressure at the cam finger to under 1,000MPa,

1. NEW ARCHITECTURE
The L411 is a clean-sheet design, with a highly integrated layout to meet the tight packaging demands of the Temerario chassis

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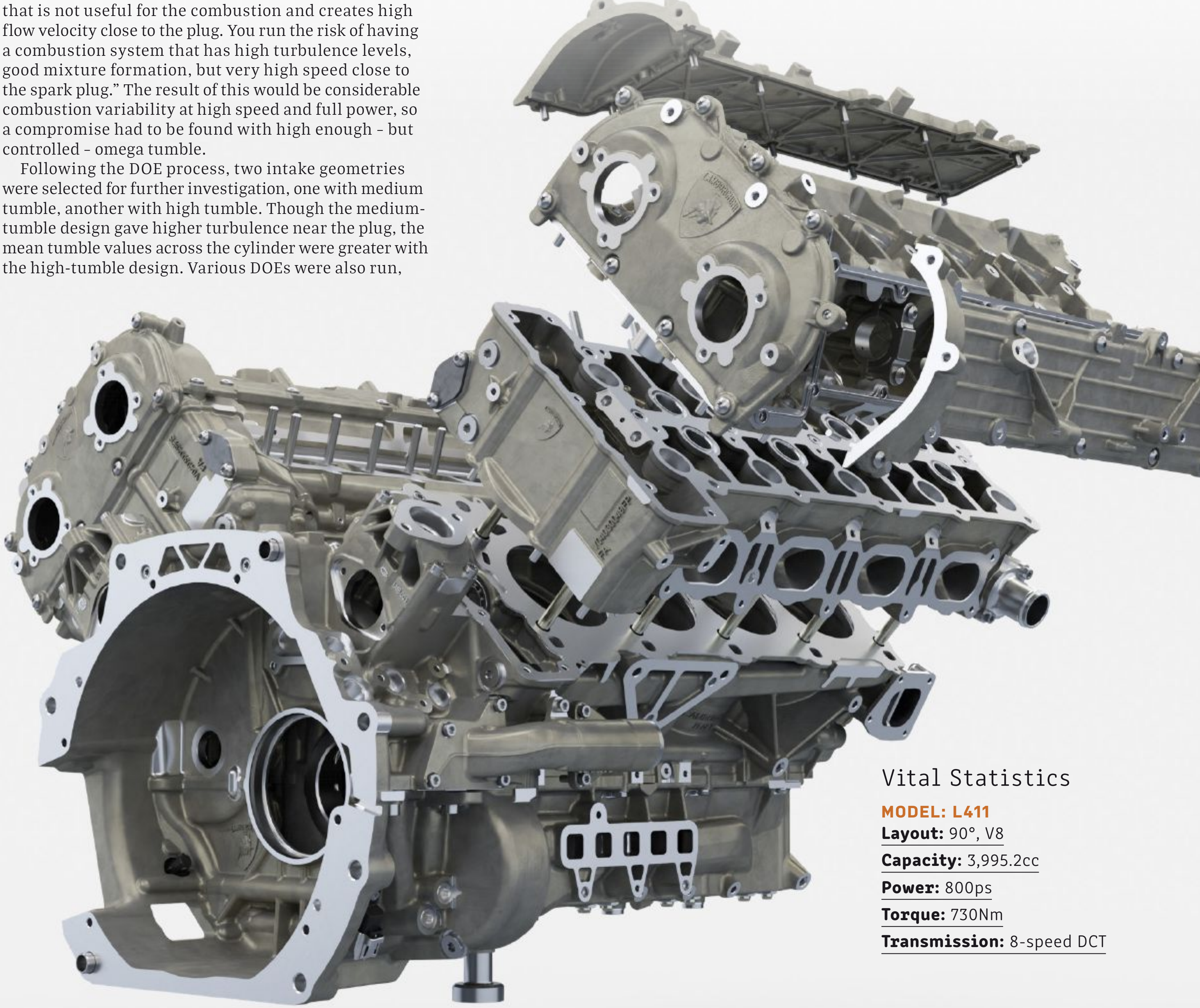


Vital Statistics

MODEL: L411
Layout: 90°, V8
Capacity: 3,995.2cc
Power: 800ps
Torque: 730Nm
Transmission: 8-speed DCT

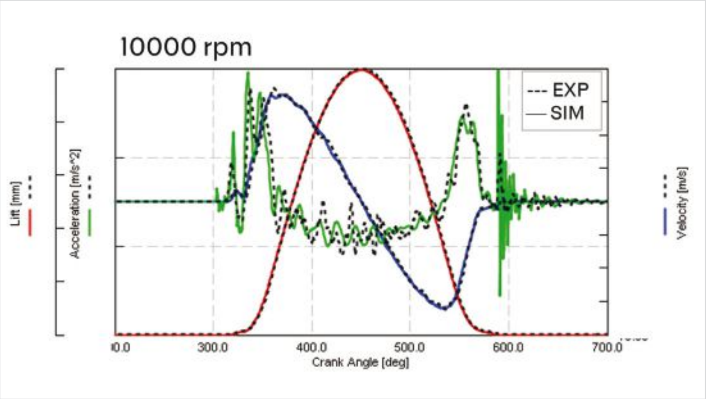


FIGURE 2. SIMULATED VERSUS ACTUAL VALVE BEHAVIOR

and DLC coating was used to improve wear resistance. Work was undertaken to refine the torsional modes of the camshaft and, once again, a compromise was required between shaft diameter – to improve stiffness – and weight. Aspects such as the cam chain tension (the L411 uses a combination of gear and chain drive for the cams) and the influence of the high-pressure fuel pumps also needed consideration. Once physical components were available, extensive testing using a high-speed test rig, with laser tracking of the valve motion, was employed to validate the simulations. As shown in Figure 2, the actual values for valve motion closely matched the virtual results.

INJECTION SYSTEM

Lamborghini's V10 used a combination of port and direct injection to achieve the emissions targets of the time. However, to meet current and future challenges, the ideal approach was GDI only for the V8. "DI is more important for a turbocharged engine; it allows better behavior in terms of knock control," states Bonandrini. "If we added PFI, maybe we could improve the performance of the engine slightly, but we have been able to attain very stable performance with just GDI."

The L411 features one injector per cylinder, centrally mounted within the chamber. These injectors are fed fuel by a large (19mm ID) fuel rail, which was sized to minimize pressure oscillations. "The injector itself was a trade-off between considering the catalyst heating [with the engine speed at around 1,500rpm and late spark advance] and the maximum power consideration," says Bonandrini. Various spray patterns and hole numbers were investigated (Figure 5). A design with six holes and a medium flow rate was found to provide the best balance across the engine's operating range. "We were able to obtain a mixture that was more concentrated close to the spark plug with a late injection, and the design also showed very good performance at maximum power, where the mixture formation is very important to keep stable combustion," Bonandrini adds.

The high-pressure fuel pumps, one per bank, are not driven in the conventional manner via the cams. Instead, they are mounted on the rear of the block, driven by a lobe mounted on the last cam drive gear. "It does not run at the traditional ratio of 0.5x engine speed," says Bonandrini. "It runs at 0.625x engine speed, which is done to obtain sufficient fuel flow as it is very hard to find a GDI pump to meet our needs, so we had to work it at a higher speed." Being able to overdrive the pump meant that auxiliary, low-pressure port injectors could be

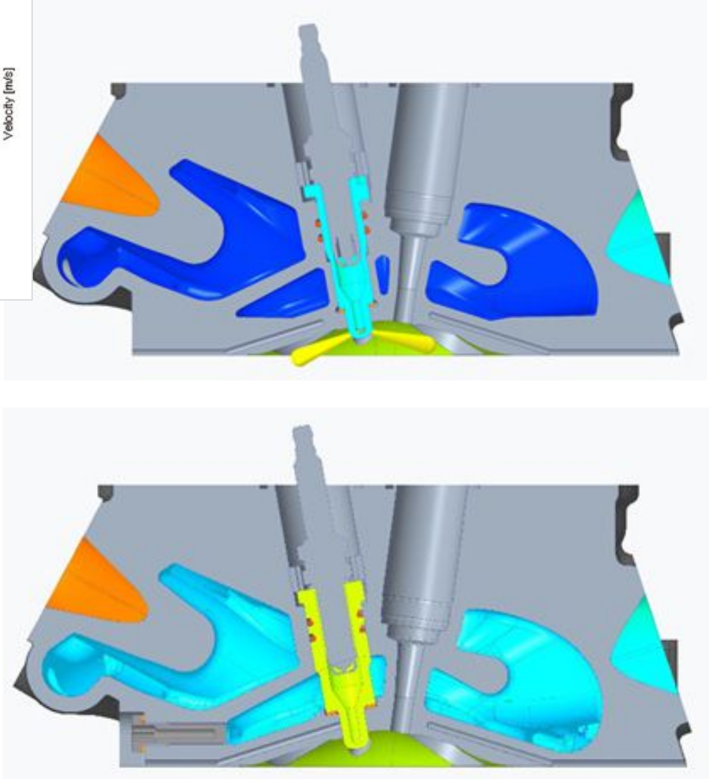


FIGURE 3. PRE-CHAMBER COMBUSTION LAYOUTS

LAMBORGHINI LOOKED AT MOVING BEYOND CONVENTIONAL GDI IN PURSUIT OF EFFICIENCY

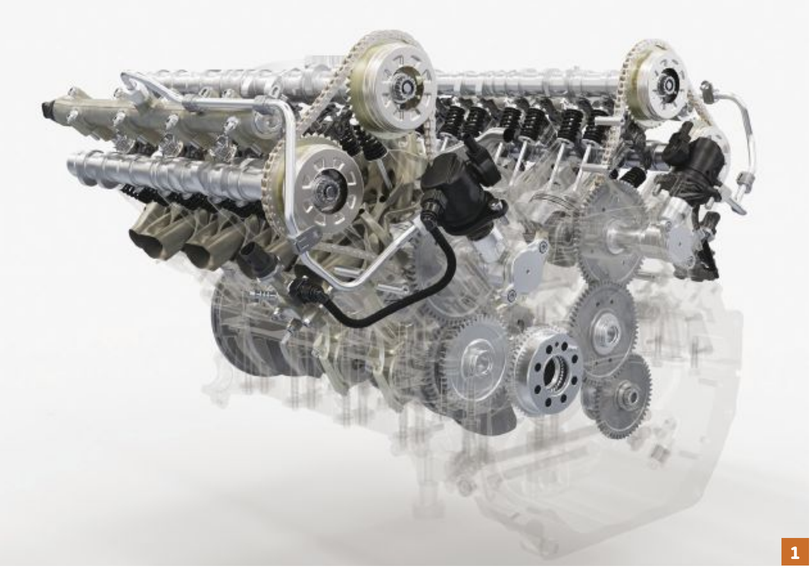
PRE-CHAMBER TRIALS

In recent years, pre-chamber combustion systems have begun to appear in some production cars, with the high-speed flame propagation they create making it possible to run at λ1 over a wide operating window, with reduced knock and EGTs. When combined with Miller cycle operation and increased compression ratios, significant efficiency gains can be made. However, this places greater thermal stress on the combustion chamber due to higher combustion temperatures.

Lamborghini analyzed two versions of a pre-chamber (Figure 3) system for the L411: a 'wet' system and a 'dry' one. The former had the pre-chamber encapsulated by the coolant within the head; the second simply machined it into the head material.

These setups were tested on the single-cylinder L411 development engine, with the wet system used in combination with a Miller cycle and increased compression ratio. The results showed a useful reduction in BSCF across the engine's operating range, and the ability to run near λ1 even at high engine speeds, the only limitation being the engine's peak operating pressure.

Though Lamborghini opted to retain traditional GDI for the Temerario, the option of a pre-chamber has been proved useful and gives room to improve efficiency if legislation demands.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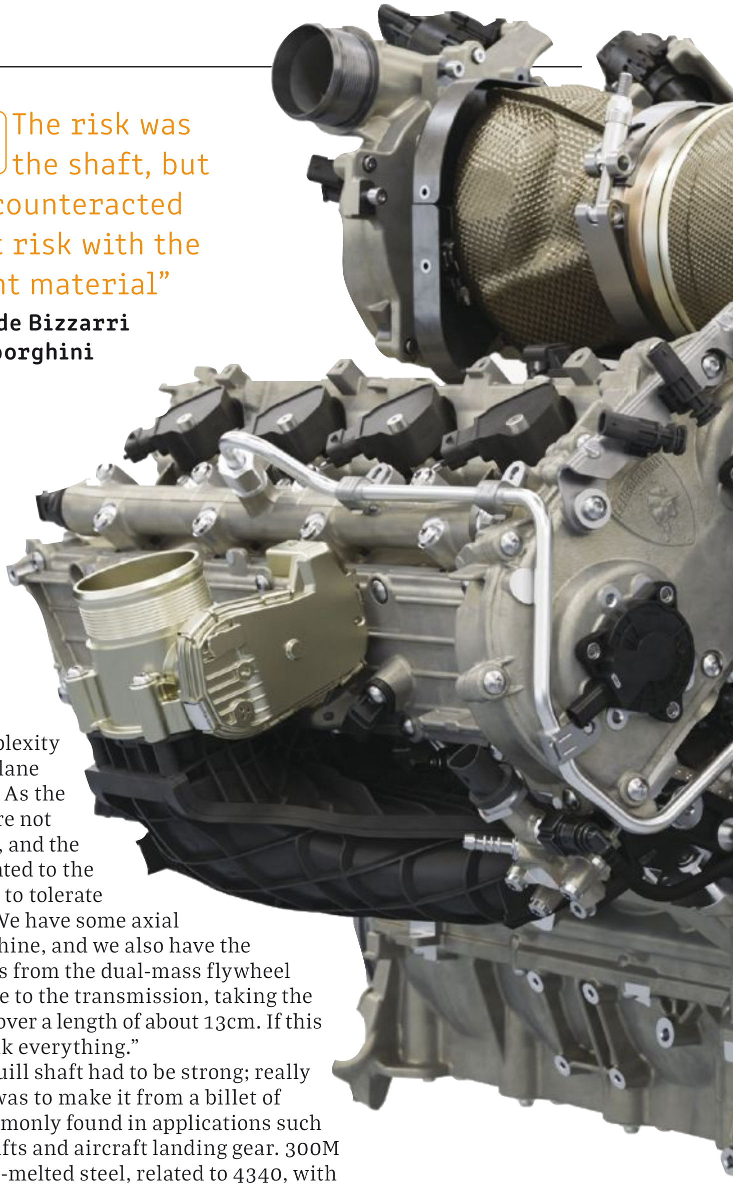
> “The risk was the shaft, but we counteracted that risk with the right material”
> **Davide Bizzarri**
> **Lamborghini**



omitted with 350-bar pressure available, and opened the potential for 500-bar injection pressures in the future.

Lamborghini investigated running injectors at higher pressures, up to 500 bar, but the gains to be made were insufficient to counter the complexities. However, the option is there if future emissions regulations require an increase. Of greater interest is the team’s investigation of the use of pre-chamber ignition (see *Pre-chamber trials*, p9).

MOTOR INTEGRATION

The L411 is possibly unique in that the P1 hybrid motor is fully integrated into the cylinder block, sandwiched between the flywheel and output shaft to the transmission. Bizzarri notes that although the Yasa-produced axial flux machine is similar to the pair used on the front axle, it has been optimized to run at higher RPM. “That meant that we had to change the grade of magnets, and the rotor design is slightly different,” he explains. The motor housing is also tailored to mate with the block; for example, its dielectric cooling fluid is routed through passages within the crankcase. The coolant pump and heat exchanger for the machine are also integrated into the ICE.

DAVIDE BIZZARRI
Head of vehicle motion at Lamborghini, Bizzarri previously worked at Ferrari and McLaren before moving to the Sant’Agata company in 2019 as head of powertrain

“The other big complexity was our use of a flat-plane crank,” says Bizzarri. As the second-order forces are not balanced in the crank, and the motor is directly mounted to the crank, it must be able to tolerate the resulting loads. “We have some axial damping of the e-machine, and we also have the quill shaft, which runs from the dual-mass flywheel through the e-machine to the transmission, taking the full 800Nm of torque, over a length of about 13cm. If this shaft breaks, you break everything.”

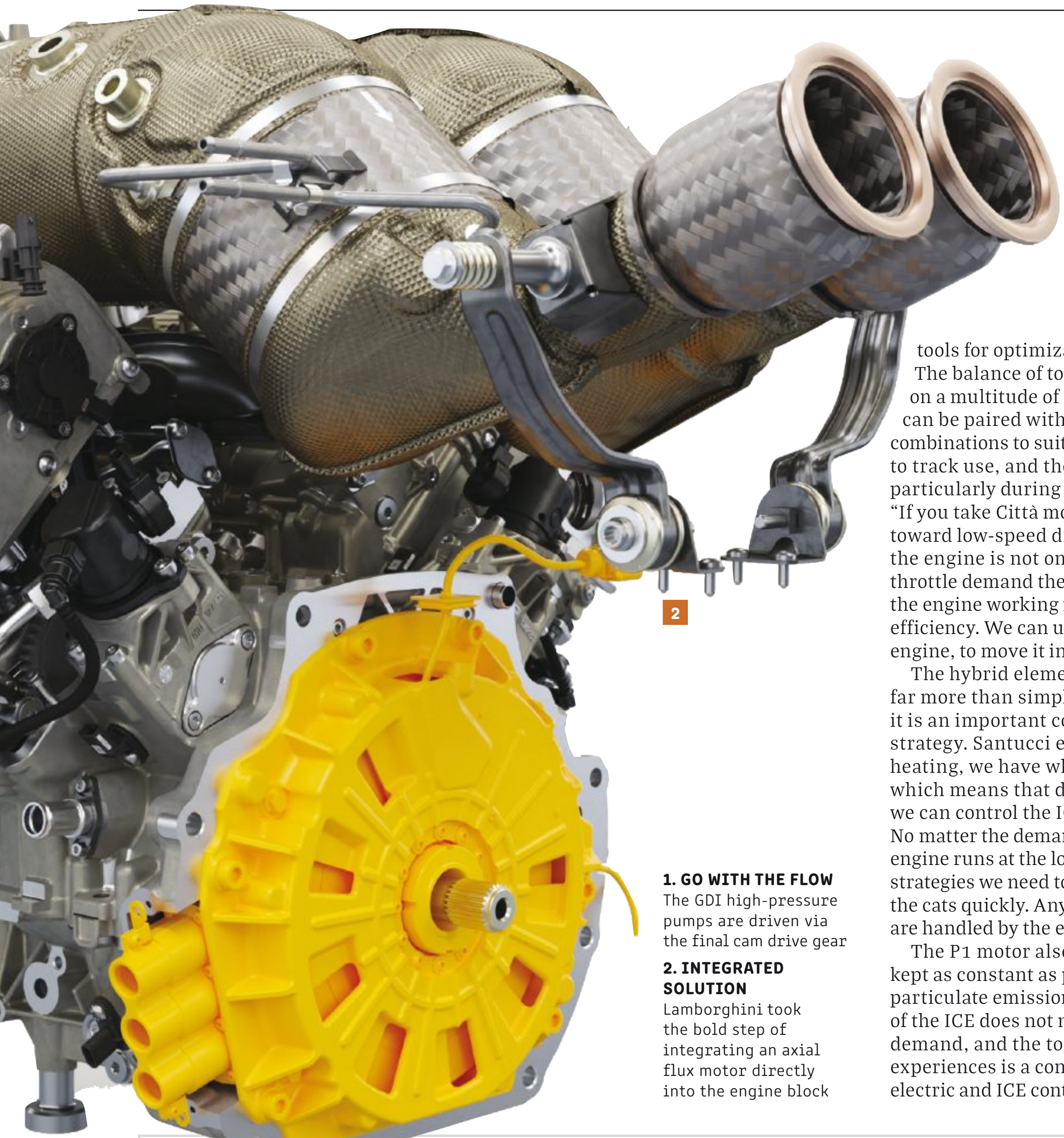
Suffice to say, the quill shaft had to be strong; really strong. The solution was to make it from a billet of 300M steel, more commonly found in applications such as Formula 1 driveshafts and aircraft landing gear. 300M is a low-alloy, vacuum-melted steel, related to 4340, with a tensile strength in excess of 300MPa; expensive but the right choice where failure of the shaft is not an option.

Of course, a longer shaft could have been used, providing a degree of compliance, but as Bizzarri points out, “There is no space. We had to control the length between the engine and the rear wheels, and integrate everything. The risk was the shaft, but we counteracted that risk with the right material.”

EMISSIONS AND CALIBRATION

The tools that have allowed Lamborghini to create a powertrain that is both emissions compliant and able to deliver the emotive engagement customers want are something of a double-edged sword, not least because the various interactions that need to be managed are vastly more complex than the ones powertrain engineers were dealing with even a decade ago. Three electric machines, a battery and a high-revving ICE all need to be perfectly coordinated. The chance of tweaking one area to hit a target and inadvertently knocking another element off-kilter is considerable.

“It’s a multidimensional problem where you can define the torque you want to split between the axles, and between the electric motors and the ICE,” notes Santucci. “You have a lot of degrees of freedom that you need to optimize in order to do this, and we rely on offline



1. GO WITH THE FLOW
The GDI high-pressure pumps are driven via the final cam drive gear

2. INTEGRATED SOLUTION
Lamborghini took the bold step of integrating an axial flux motor directly into the engine block

tools for optimization that we developed in-house.”

The balance of torque provision shifts depending on a multitude of factors. Three core driving modes can be paired with different energy use modes in 13 combinations to suit every condition from urban cruising to track use, and the demands of emissions control, particularly during warm-up are also accommodated. “If you take Città mode, for example, which is geared toward low-speed driving, we can define an area where the engine is not on,” says Santucci. “When driver throttle demand then increases, what you tend to have is the engine working in an area of the BSFC map that is low efficiency. We can use the electric motor to add load to the engine, to move it into a more efficient operating area.”

The hybrid element of the powertrain also delivers far more than simple torque infill under acceleration – it is an important component of the emissions control strategy. Santucci explains, “If you look at the catalyst heating, we have what we call a stable torque strategy, which means that during the catalyst heating phase we can control the ICE at a torque we predetermine. No matter the demands from the driver and so on, the engine runs at the load, spark advance and ignition strategies we need to minimize emissions and light off the cats quickly. Any throttle demands from the driver are handled by the electric motors.”

The P1 motor also enables the load on the engine to be kept as constant as possible, which is ideal for controlling particulate emissions. This means that the torque output of the ICE does not necessarily follow that of the throttle demand, and the torque at the axle that the driver experiences is a constantly varying combination of the electric and ICE contributions. “Once the capability of the

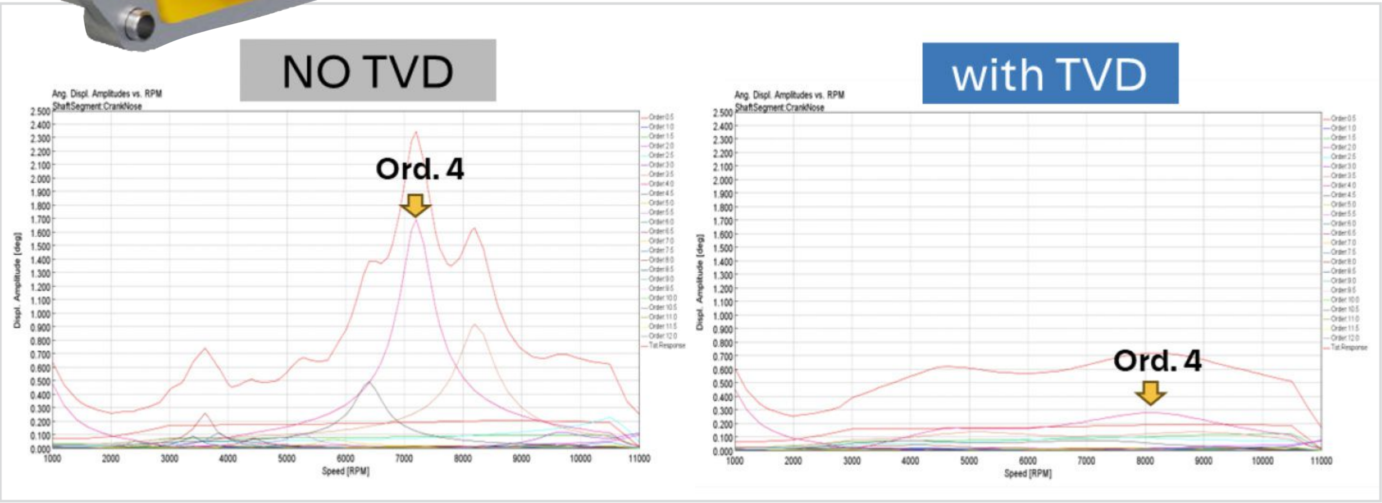


FIGURE 4. TORSIONAL VIBRATION WITH AND WITHOUT TVD

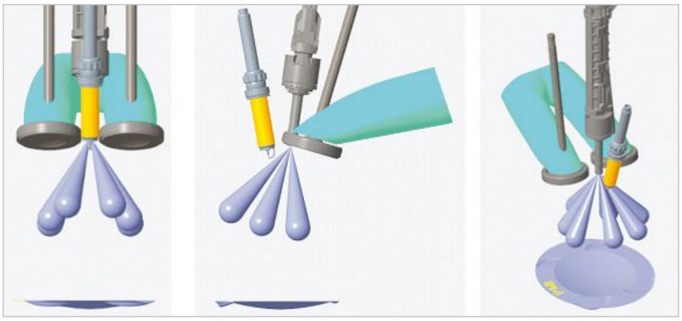


FIGURE 5. GDI INJECTOR SPRAY PATTERNS

electric motors is exceeded, we then start to ramp in the ICE," says Santucci. "It is degrees of freedom like this that the hybrid provides, which we didn't have in the past and makes our lives easier."

He reinforces that coordination between the various powertrain groups has been vital to ensure that changes made in one area do not affect another – for example, reliability. Meeting drivers' expectations is also very high on the priority list. "There has been very close collaboration to minimize any transitions the driver may perceive," he notes. "For example, the phases where we start the engine, or where we transition from only driving with the front axle in EV, to four-wheel drive with the ICE, need to be as seamless as possible."

In isolation, the L411 V8 that Lamborghini has created is a masterpiece, pushing the envelope of what is possible with road-going combustion technology. However, it is just one piece of the intricate puzzle that makes up the Temerario hypercar. In the next issue of *APTI*, we will take a close look at the wider hybrid system, the control strategies and the possibilities these open up from a vehicle dynamics perspective. ⦿

APTI *would like to thank Davide Bizzarri and his colleagues, Giovanni Bonandrini, Luca Rizzi, Emilio Palis and Alberto Santucci, for the exceptional level of input they provided for this feature*

HOW TO BESTOW A TURBOCHARGED V8 WITH A SOUNDTRACK THAT STIRS THE SOUL

THE WAIL OF THE BEAST

Aurally, the Temerario has big shoes to fill. But how can the soulful wail of an NA V10 be matched when a pair of turbos are stealing all that exhaust energy? Not to mention stricter legislation around drive-by sound levels for new vehicles in some markets, and GPFs muting any higher frequencies that remain.

Fortunately, Lamborghini was able to engineer a solution that keeps exterior noise to acceptable limits while refining the in-cabin soundscape. This is achieved with what the car maker dubs the 'sound symposer', which brings the intake sound of the L411 into the cabin. Rather than relying on a synthesized noise piped through the car's infotainment system, Davide Bizzarri's team wanted to keep the sound analog. An outlet from the intake manifold feeds to a plenum that is split in two by a membrane with its stiffness engineered to resonate at a carefully tuned frequency. A throttle valve positioned between this membrane and a tuned-diameter and length pipe (which feeds into the cabin) means the system can be activated when in a driving mode that warrants greater aural stimulation.

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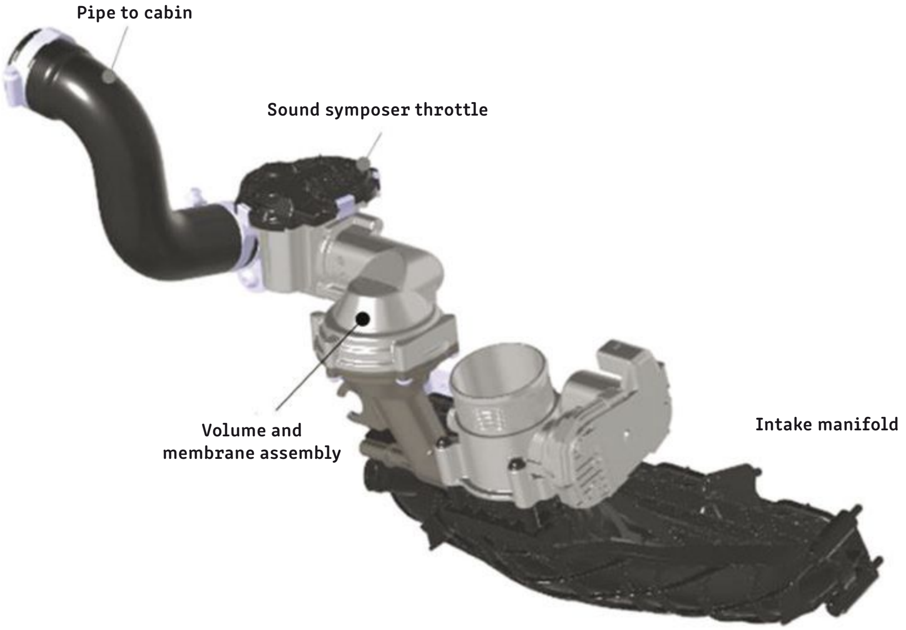

1. SOUND SYMPOSER
Lamborghini has been able to maintain the in-car aural drama, without breaking any noise legislation or resorting to synthesized sounds

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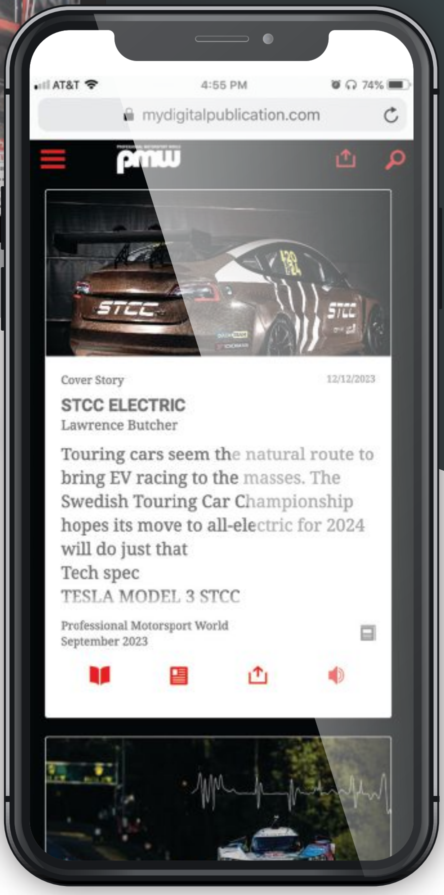
12 TECH INSIDER: NASCAR EV PROTOTYPE
TECH INSIDER: NASCAR EV PROTOTYPE 13

Top of the stocks

NASCAR is the home of the V8, but the series' latest special project set out to investigate the potential for electrification in oval racing

"WE WANT TO BE IN THE DRIVER'S SEAT AND MOVE FORWARD WITH OUR OEM PARTNERS"



Cover Story 12/12/2023

STCC ELECTRIC
Lawrence Butcher

Touring cars seem the natural route to bring EV racing to the masses. The Swedish Touring Car Championship hopes its move to all-electric for 2024 will do just that
Tech spec
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HYDROGEN

JCB'S GROUP DIRECTOR OF SPECIAL PROJECTS, TIM BURNHOPE, DETAILS THE DEVELOPMENT OF THE CONSTRUCTION EQUIPMENT GIANT'S FIRST COMMERCIALLY AVAILABLE HYDROGEN ENGINE

Words: Chris Pickering

HYDROGEN
JCB

HOPES

It's not every day that you see a JCB driving over Westminster Bridge in London. But the sight of the green and white digger cruising toward the UK's Houses of Parliament held special significance on April 29, 2025, because the company had just been granted government permission for its hydrogen-fueled vehicles to travel on public roads.

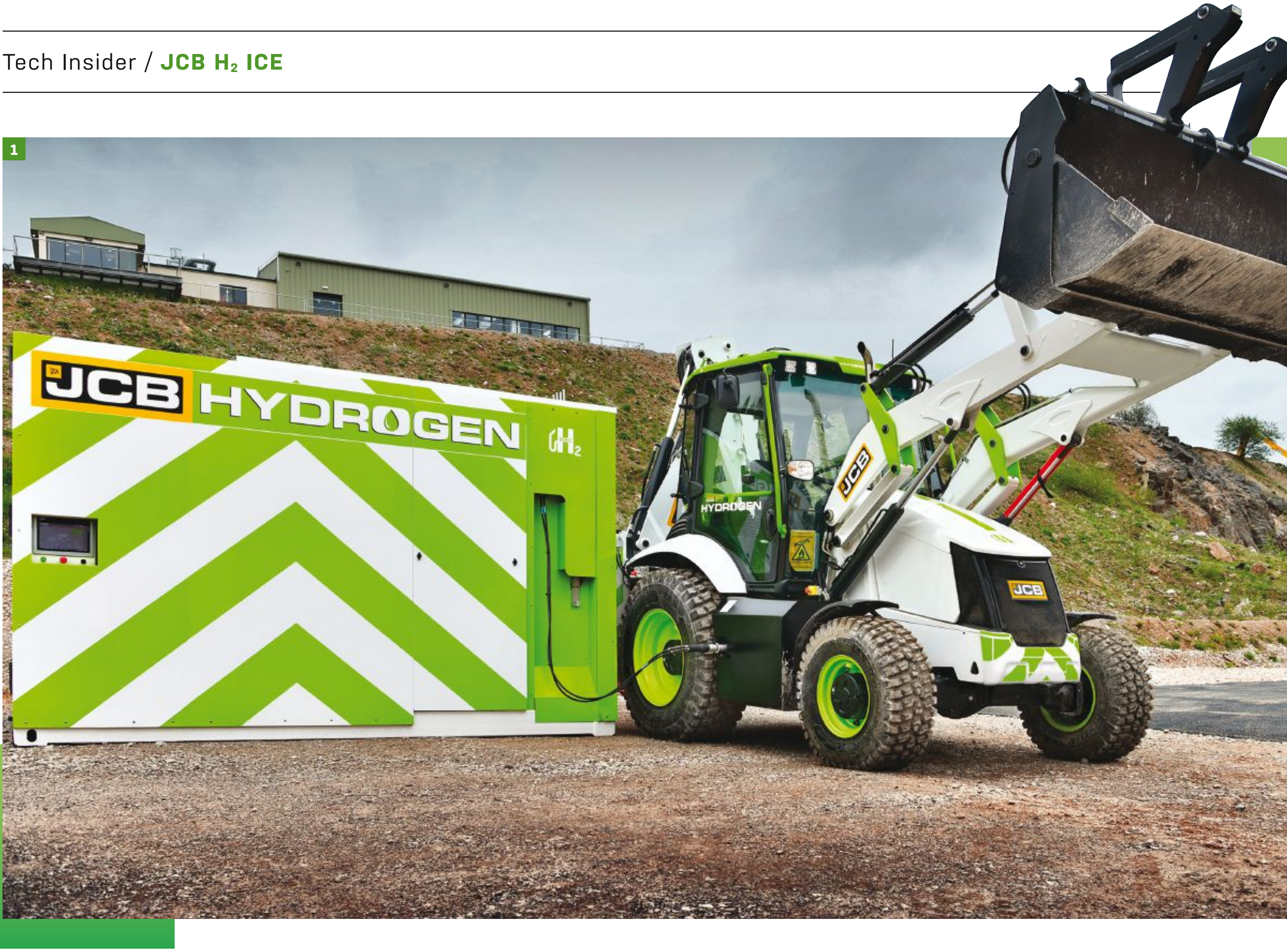
This followed an announcement in January that JCB's hydrogen combustion engine had been approved for sale by 11 licensing agencies across Europe. JCB is believed to be the first construction equipment company in the world to develop a hydrogen combustion engine in its line-up, following a £100m (US$132m) development project that spanned three years and involved 150 engineers.

The origins of the project go back far further, though, as JCB's group director for special projects, Tim Burnhope, explains: "We began installing a telematics system across our entire fleet in 2010. We now have over 500,000 vehicles equipped with the system, and one of the things it measures is fuel consumption, and hence how much CO_2 the fleet is producing. That transformed the way our engineers thought about the products."

> "We launched our first electric mini excavator in October 2019, and now produce 22 different models"

Since then, JCB has focused on efficiency improvements in its existing technology, as well as exploring new concepts. This began with simple steps, such as reducing the number of sharp bends in the vehicles' hydraulic pipes to reduce parasitic losses, but it has led to the development of a whole new powertrain technology.

Hydrogen is by no means the only option that the company is pursuing. "Like everybody else, we got very excited about electric products," Burnhope says. "We launched our first electric mini excavator in October 2019, and we've gone on now to produce 22 different models, selling around 35,000 worldwide so far. But these tend to be compact machines, used in areas where the infrastructure is already present, so there's electricity at the point of use. A lot of them are also used indoors in places such as underground sites or car parks, where noise and air quality are particularly critical."



1. ON-SITE
One of the key appeals of hydrogen for JCB is its ability to provide emission-free fuel in remote locations

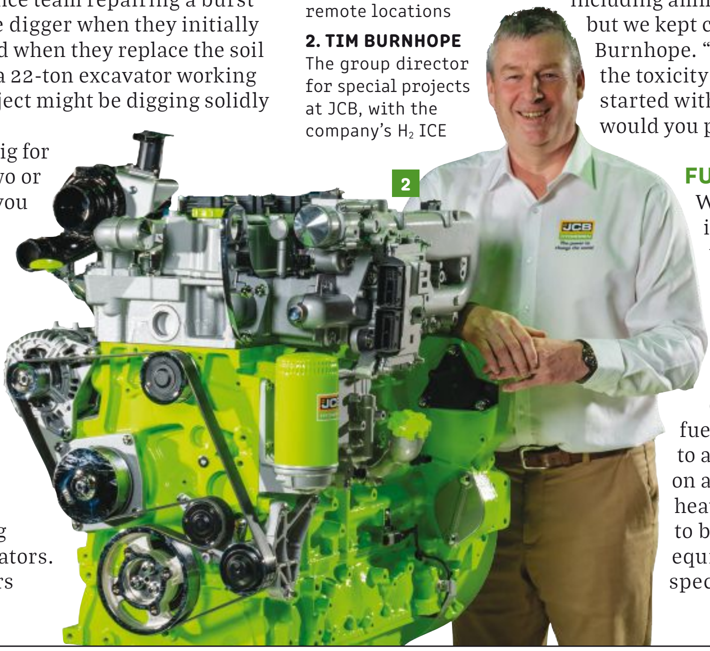
SCALABILITY

The challenge with electric diggers, as with battery-electric road vehicles, comes with scaling up. A two-ton mini digger only tends to work for a couple of hours each day. For example, a maintenance team repairing a burst water pipe might only use the digger when they initially dig down to reach the pipe and when they replace the soil again at the end. In contrast, a 22-ton excavator working on a major infrastructure project might be digging solidly for 12 or 15 hours.

"A 22-ton excavator could dig for two or three hours a day on two or three tons of batteries. But if you want to work all day you're looking at maybe 11 tons of batteries. Suddenly, a product that might cost £150,000 [US$198,000] in the diesel world becomes £500,000 [US$660,000]," notes Burnhope.

The availability of electricity was another issue, with several customers admitting that they felt uncomfortable about charging the diggers with diesel generators. Conventional diesel excavators remain on-site and the fuel is brought in by tankers, so the industry was keen to find a net zero approach that followed a similar process.

"We looked at a number of alternative fuels, including ammonia, HVO, biodiesel and e-fuels, but we kept coming back to hydrogen," explains Burnhope. "With ammonia, for instance, you have the toxicity to consider; with e-fuels you've already started with a large quantity of hydrogen, so why would you process it further?"



2. TIM BURNHOPE
The group director for special projects at JCB, with the company's H_2 ICE

FUEL CELL TRIALS

With electric powertrains already in use in some of JCB's smaller applications, the logical next step initially appeared to be a hydrogen fuel cell. A prototype was built that showed some promise, but it also highlighted several issues.

The cooling requirements were found to be substantial, yet the comparatively low temperatures that fuel cells operate at (60-75°C, as opposed to as much as 125°C for a diesel digger on a hot day) made it hard to dissipate the heat. This meant the cooling pack needed to be three times the size of its diesel equivalent. To prevent short circuits, specialist deionized coolant needed to

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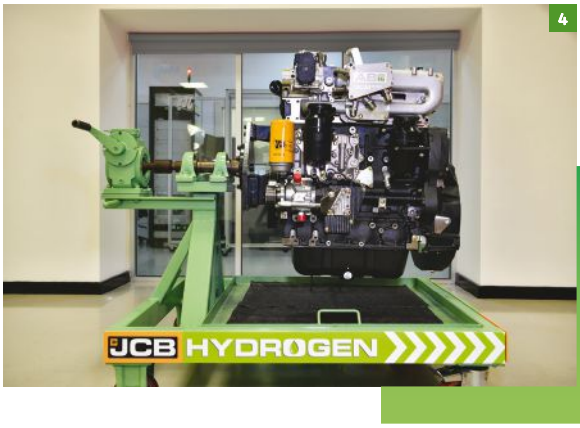

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3. FACTORY FRESH
JCB Power Systems in Derbyshire is the UK base for JCB's engine production

4. PROOF OF CONCEPT
A team of engineers from backgrounds as diverse as F1 and the motorcycle industry was tasked with designing an engine to meet or exceed the capabilities of JCB's 55kW diesel

> "We needed to get the temperature and the pressure down to meet our emissions targets"

be used. Inadvertently filling the system with regular water could lead to costly repairs, which is a significant concern in a market where resale values and total cost of ownership are key.

Another issue is that digger powertrains typically go through a series of aggressive transients as the hydraulic demand fluctuates during digging. Fuel cells work best at constant load, so JCB employed a complex energy management system with power-dense lithium titanate batteries to smooth out the load profile. However, this of course added further cost and complexity.

Despite these setbacks, JCB remained committed to the rapid refueling capabilities and zero carbon emissions offered by hydrogen, so the decision was taken to switch to a combustion engine.

A crack squad of engineers was assembled from backgrounds as diverse as Formula 1 racing and the motorcycle industry. Their brief was to design an engine that would meet or exceed the power and torque capabilities of the company's standard 55kW diesel unit. They used the bottom end, including the block and crankshaft, from JCB's existing 4.8-liter diesel engine, but developed an all-new spark ignition architecture for the top end.

"The biggest technical challenge was the combustion chamber," explains Burnhope. "We needed to get the temperature and the pressure down to meet our emissions targets, so we went through 167 iterations of the combustion chamber design."

JCB
HYDROGEN
ZERO EMISSIONS
FUEL CELL TECHNOLOGY
JCB

1

1 & 2. ROAD TO DECARBONIZATION
JCB has taken a multipronged approach to decarbonizing its product line, including fuel cells

One of the first challenges was to get the hydrogen to mix homogeneously with the air, reducing localized mixture variations and hot spots. Hydrogen ignites very easily, but it can burn across a wide range of equivalence ratios, leading to very different in-cylinder conditions.

“A lot of the early experiments around hydrogen [elsewhere in the industry] used modified petrol engines – most of them naturally aspirated – and they ran much richer and at much higher temperatures than we do today,” comments Burnhope. “If you can reduce those temperatures, there comes a point where the NO_x emissions suddenly drop right down. As it happens, hydrogen is the only fuel that can combust below that limit, but it needs careful management.”

Chemical compatibility was another consideration, with hydrogen known to cause problems with permeability and embrittlement in some materials. The engineering team’s response was to work through the design systematically, identifying the requirements for every component.

“There’s something like 700 parts in the engine, but only a limited number of those actually come into contact with concentrated hydrogen. The moment it mixes with air, a lot of those issues go away,” notes Burnhope. “The main places are the tanks and the supply lines. Once you get into the engine it’s less challenging. And, of course, we don’t tend to use as many light alloy materials as you might find in a passenger car engine.”

JCB worked with several companies on the development of the tanks. Since the beginning of the project, Burnhope says, the maturity of hydrogen storage technology has improved considerably.

“We’ve now got a lot of large-volume organizations – experienced Tier 1 suppliers that have maybe been involved in the car world before – starting to think about hydrogen tanks. And with that come the pipework and regulators.”

JCB also has its own in-house expertise in pressurized fluids. The company’s hydraulic systems run at 350 bar, so the same pressure was chosen for the onboard hydrogen tanks. Upon leaving the tank, a regulator takes the pressure down to less than 20 bar for the fuel lines into the engine.

The gas can be stored and transported at up to 700 bar and then cascaded from one vessel to another to depressurize it on-site. This makes it a relatively simple process from a technical perspective, but the focus has shifted to the logistics and the economics of hydrogen, Burnhope explains.

“What we’re really looking at now is how we transport hydrogen from the production site to the machines and how we refuel,” he says. “Just before Christmas we went to 10 different customer jobsites, using green hydrogen produced at the Tyseley Energy Park in Birmingham. We created a refueler that can be mounted on the back of a pickup, drove that to the sites and refueled the machines. The process worked really well. It’s how we move to mass adoption of that technology that’s the challenge now.”

JCB’s hydrogen engine is not yet available commercially. But its use in a variety of customer trials, alongside the company’s diesel and electric offerings, showcases what Burnhope describes as “the art of the possible”.

“I think the world is now getting to grips with what works and what doesn’t work,” he says. “What’s important for our industry is that we’ve demonstrated the three technologies of battery, fuel cell and hydrogen combustion engine, and that will help regulators define the right technology. Maybe the car industry didn’t get that opportunity; everyone focused on battery-electric powertrains while other technologies were dismissed.”

> “What’s important is that we’ve demonstrated the three technologies of battery, fuel cell and hydrogen combustion engine”

Only time will tell what the balance of these technologies will look like in the future. But JCB’s commitment to hydrogen will surely help shed some light on these questions for the construction industry. ⦿

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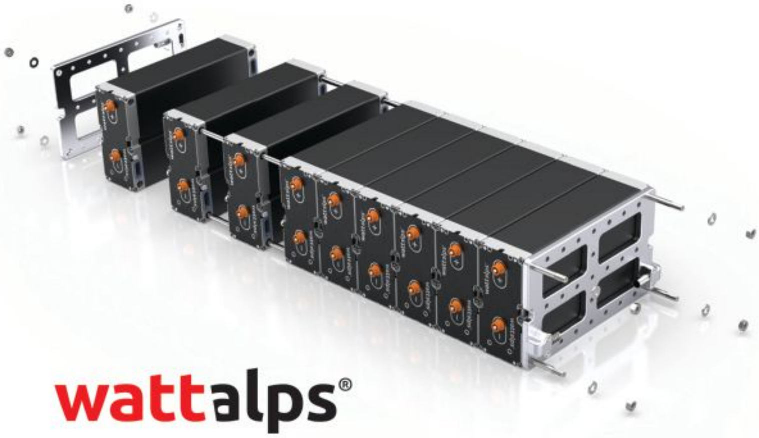

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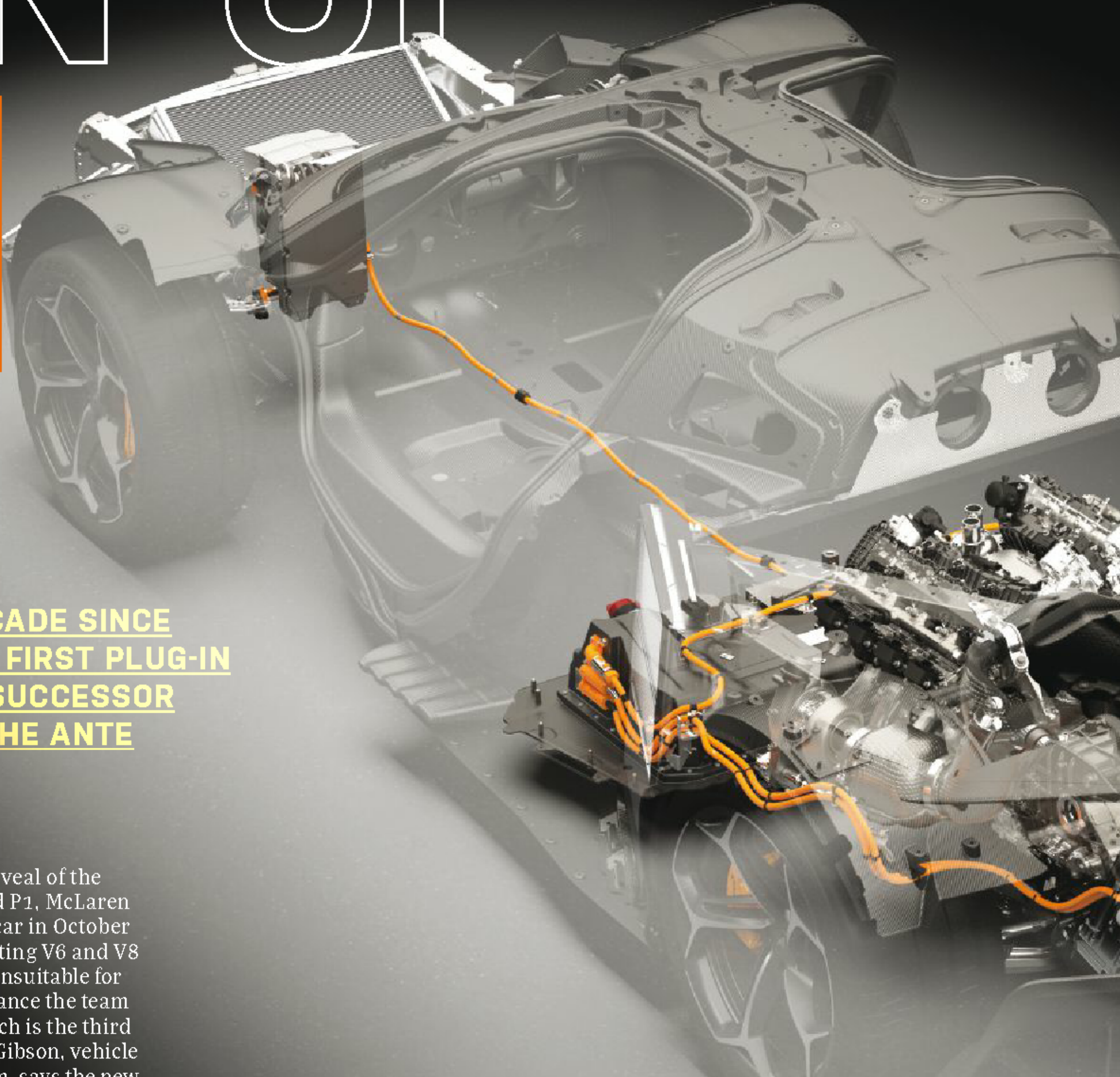


IT HAS BEEN OVER A DECADE SINCE McLAREN PRODUCED ITS FIRST PLUG-IN HYBRID. NOW, THE P1'S SUCCESSOR – THE W1 – HAS UPPED THE ANTE

Words: Trinity Francis

Eleven years after the reveal of the groundbreaking hybrid P1, McLaren unveiled its W1 hypercar in October 2024. The brand's existing V6 and V8 engines were deemed unsuitable for the power and performance the team was looking for in the P1's successor, which is the third installment in McLaren's '1' series. Alex Gibson, vehicle line director for McLaren W1 and platform, says the new MHP-8 engine "had to be more efficient in terms of power-to-weight as well as meeting future worldwide legislative requirements".

He continues, "We also wanted to push the rev limit higher than before, so we took the decision to develop a clean-sheet engine design and unlock the ability to extend the performance envelope. The fundamental requirements have led us to a four-liter flat-plane crank, twin-turbocharged V8."

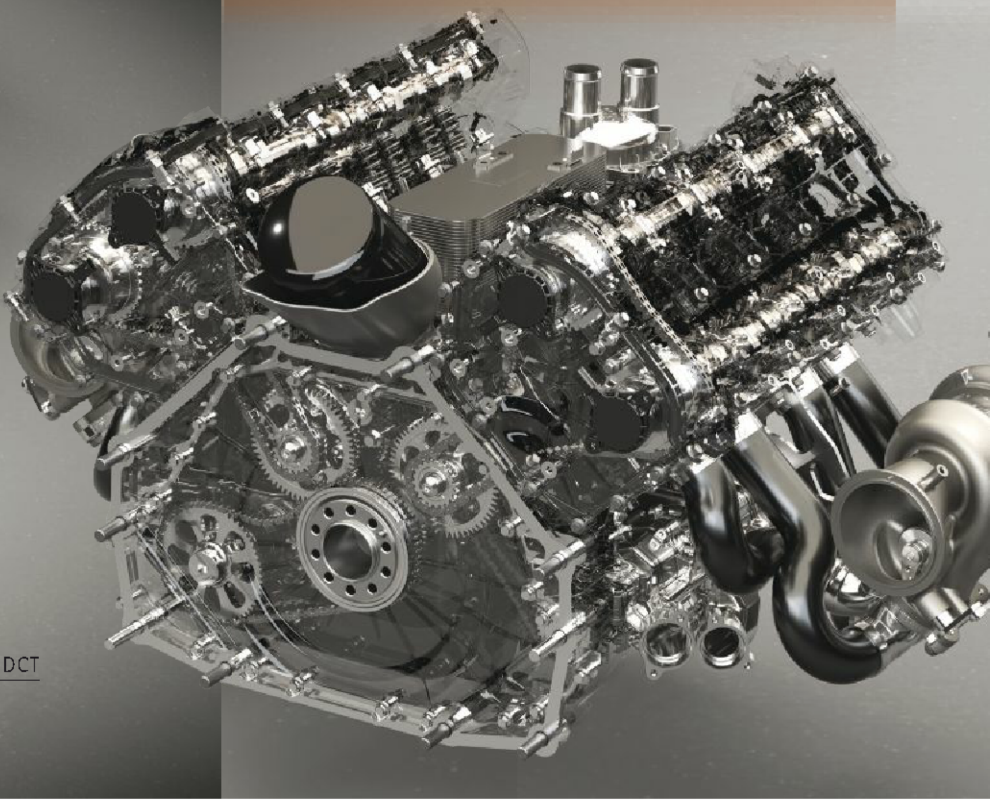
Paired with an electric drive unit powered by a 1.384kWh battery, the hybrid powertrain delivers 1,275PS and 1,340Nm of torque. The red line is found at 9,200rpm, although as Richard Jackson, chief powertrain engineer, says, "We didn't need to add 700rpm to make the power – we did that purely to excite the driver."

ENGINEERED SOUND

Striking the correct NVH balance for a powertrain that had to stir the soul yet still show refinement was a complex task. "Extending the [engine] speed range, we needed a valvetrain that allowed us to really push the limit," explains Richard Jackson. "One of the technologies we've applied is hollow intake valves. Obviously, at higher speed we've got much higher inertia forces, so a stiffer crankshaft, stronger cranktrain components.

"We've also used, for the first time, an internal torsional vibration damper on the front of the crankshaft, which is oil cooled to keep the silicone in its optimum operating range. Then the next stage is building that crescendo and the sound enhancement to that increased rev range. One of the key areas of development was tuning the exhaust system at the manifold, so with the equal length runners, we tuned the length of the manifold to really build the noise and the sound as you go toward the rev limit."

The powertrain is soft-mounted for comfort, but vibration transfer to the cabin is said to increase with the rising exhaust note. No artificial sound generation is used. Instead, McLaren favored hardware tuning to achieve the desired accompaniment to the intake and exhaust sounds.



Vital Statistics

MODEL: MHP-8
Layout: 90° V8
Capacity: 3,998cc
Power ICE: 920ps
Power hybrid: 347ps
Torque: 1,340Nm
Transmission: 8-speed DCT
Battery: 1.384kWh

Discussing key developments to maximize power, Jackson says, "The combustion system is at the heart of the engine. The key thing here is the optimization of the air into the cylinder through the port. We used extensive CFD modeling with moving mesh to optimize the port design and the combustion chamber shape."

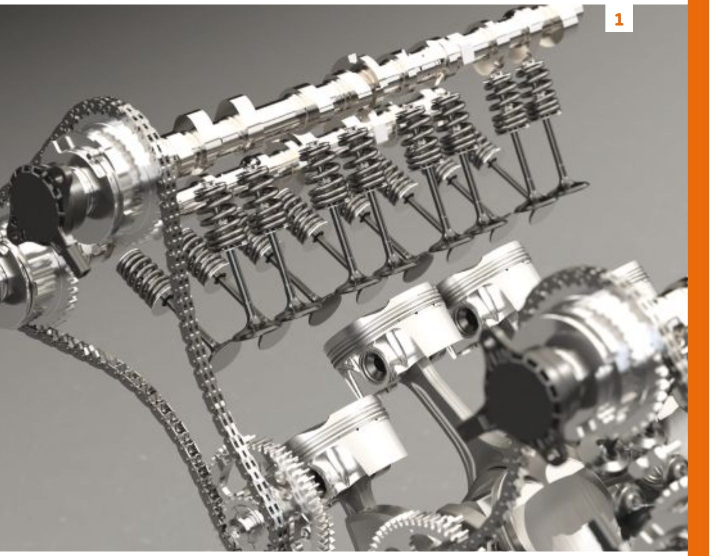
In terms of cooling, the focus was around the combustion chamber in the cylinder head. Jackson says, "We used 3D-printed core technology, which allows us to get the coolant much closer to the most thermally loaded areas, much more than we could do with conventional sand core technologies."

Making its first McLaren appearance on the MHP-8 engine is a combination of gasoline direct injection (GDI) and port fuel injection (PFI), with the 350 bar GDI system helping to optimize emissions. Jackson explains, "Again, lots of work with CFD, looking at the targeting of the injector spray within the cylinder, the hole size, the duration of the injection in the cycle. We use triple injections at times in the critical emission zone to get that correct air-fuel ratio to get a good start to the combustion."

McLaren only turns to the port fuel injection at full load. "What this allowed us to do was minimize the GDI injector size, and it gives us more time to mix the fuel and air at peak power and very high engine speeds," Jackson notes.

> "We used 3D-printed core technology, which allows us to get the coolant much closer to the most thermally loaded areas much more than we could do with conventional sand core technologies"

1. COMPACT FEATHERWEIGHT
The MHP-8 is 10kg lighter and 30mm shorter than its predecessor



LIGHTWEIGHTING

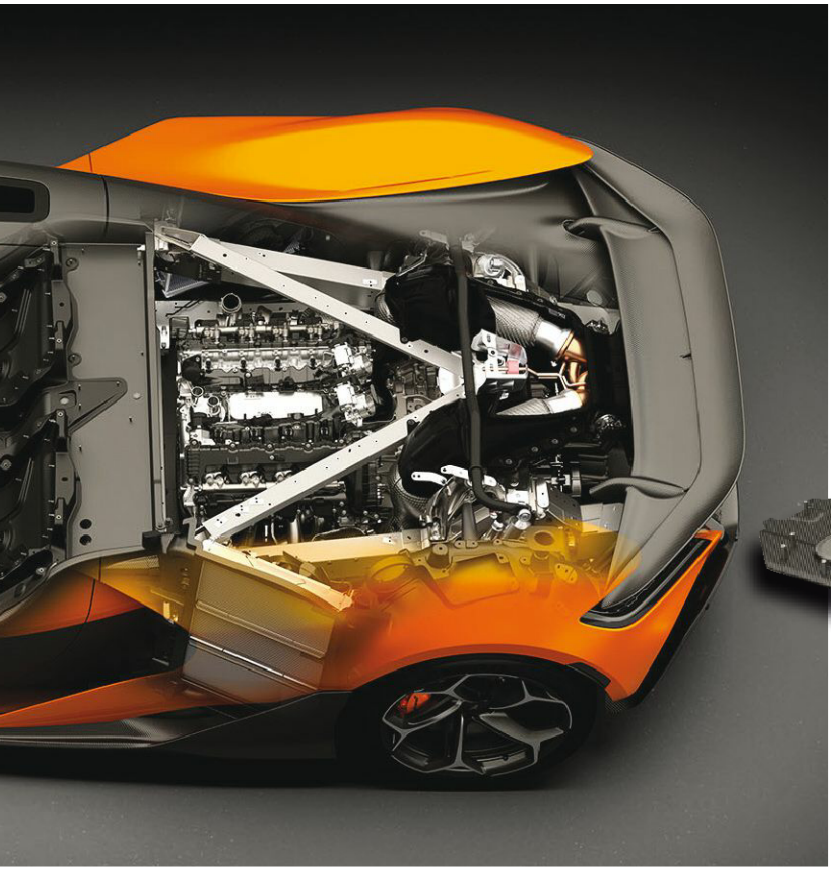
Compared with McLaren's M840T V8 engine, the new MHP-8 is 10kg lighter and 30mm shorter. The latter was achieved by reducing the bore size by 1mm and creating a compact cam drive package at the rear. Jackson says, "Other technologies that we've applied are plasma-sprayed bores instead of separate liners, and we used 3D-printed sand cores to optimize strength and weight."

On the intake system, a small, compact manifold made of GRP offers additional weight savings. Jackson adds, "The other benefit is it's very low down, so we've reduced the overall height, allowing us to mount the air filter directly over the engine, which reduces the weight of a duct but also improves the efficiency and the pressure drop and performance."

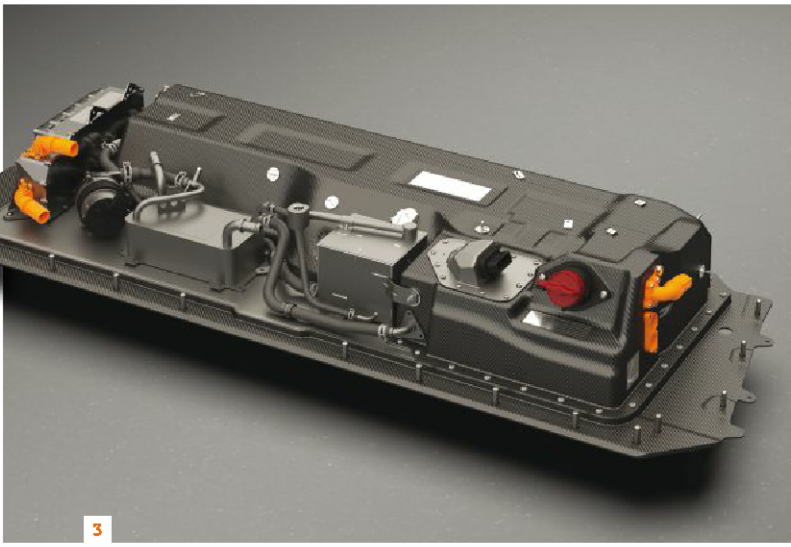
The hollow intake valves allow for lighter springs, with a knock-on effect on the rest of the valvetrain. "We've reduced weight by going hollow on the camshaft, and we've got lighter, faster-acting cam phases, benefiting both weight and transient response," Jackson notes. Although the hybrid system adds weight overall, it means the engine can be made lighter by eliminating the need for a starter motor, alternator and associated componentry.

Gibson summarizes, "It is the attention to detail on every part of the design, looking at optimal materials for weight not only in the powertrain but the whole car.

"There's extensive carbon fiber; the 3D printing of the suspension components has yielded huge weight savings; we've got hollow castings in the rear frame of the car. In the powertrain, it's the fine details of weight saving in how we've designed the cooling jacket in the block to minimize the bore spacing, the amount of aluminum in the castings. Everywhere you look, there are features for weight saving or to enhance the cooling performance so we don't need to add weight elsewhere."



> “The torque from the e-motor is fed through any of the even gears in parallel with the engine feeding torque through all eight gears”



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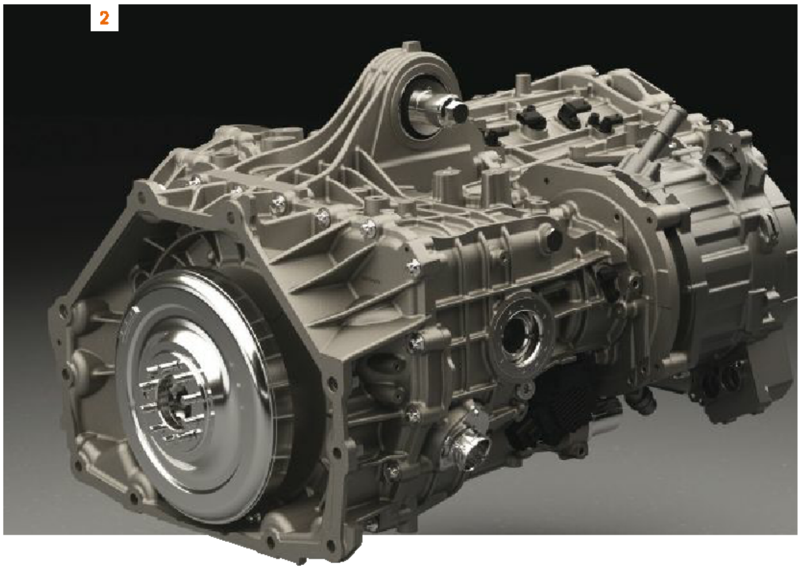

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2. HYBRID POWER
The DCT also incorporates the hybrid motors

3. BATTERY PUNCH
McLaren opted for power density over energy density when it came to cell chemistry

HYBRID COMPONENTS

Paired with the new ICE, McLaren has used a relatively low-energy-density battery pack with the focus on power density. The battery is a continuation of technology that began on the company’s Speedtail but with the pack weight reduced and cooling enhanced for track use. Harnessing experience gained in motorsport, the McLaren pack features 12 modules with immersion cooling using dielectric fluid, run through a dedicated coolant circuit.

The inverter is integrated into the rear of the radial flux e-motor with an all-up weight of 20kg – around 50% lighter than the system used on the Speedtail. Jackson notes, “The e-module is now mounted on the side of the transmission and feeds the torque downstream of the clutches; this is key to unlocking the torque capacity. Now, we can put 900Nm of torque through the clutches and an additional 440Nm downstream of the clutches.

“The torque from the e-motor is fed through any of the even gears in parallel with the engine feeding torque through all eight gears. That huge amount of torque and power is then fed through an [electronically controlled] differential to the rear wheels. We don’t have a physical reverse, we use the e-motor.” Although the battery can be plugged in for conditioning, the system is designed to maintain a base level of charge to facilitate reversing.

With the launch of the W1 and MHP-8 engine, McLaren is resolutely committed to enhancing the combustion engine as far as regulations and technology will allow. Short to medium term, the brand expects its product range to be dominated by hybrid powertrains, with this hybrid V8 underpinning future generations of McLaren supercars. ⦿

VOLKSWAGEN ID. BUZZ

Single PSM

Expectations for the ID. Buzz were high – and understandably so. It's a reincarnation of the T1, a beloved icon brought back to life with modern technology. VW made bold promises, and in *APTI*'s opinion, it delivers on all fronts. It looks great, it's efficient, it's fun to drive, all while retaining the spirit of the original van.

The ID. Buzz isn't exactly subtle – and it's a common sight, from urban streets to highways. Its styling and funky aesthetics really are easy to fall in love with; the electric van strikes a perfect balance between retro charm and sleek contemporary design. The real question is, do the engineering and technology match that charm?

Built on the German guru's purpose-designed MEB battery-electric platform, the version *APTI* tested was equipped with a 77kWh (gross 82kWh) lithium-ion battery featuring 12 modules. This battery powers a 204ps motor driving the rear wheels. Volkswagen claims the ID. Buzz is "a very agile vehicle" – and it is. The electric motor delivers its maximum torque of 310Nm from a standing start. With the battery mounted low in the sandwich floor, the vehicle benefits from a very low center of gravity.

Even in 2025, there remains some skepticism about the real-world range of EVs, especially MPVs like the Buzz. VW cites a WLTP range of up to 410km. During *APTI*'s test drive, which included a 127km trip taking in motorways and rural roads while transporting a sofa, the Buzz was truly put through its paces and the real-world range was found to be accurate. What's more, it was handed over from one member of the *APTI* team to another with near-zero range on the clock, yet somehow the ID. Buzz made it the 18km to the nearest fast charger. Impressive stuff indeed.

Of course, the powertrain is just one part of the engineering story behind the T1 revival. Full of personality, the ID. Buzz is nothing but pleasure. Ride quality and dynamics are on point too; it feels stable and responsive both on open roads and in traffic. As a complete package, it is loved by adults and kids. For *APTI*, the ID. Buzz isn't just a strong remake – it is, quite frankly, one of the best vehicles launched in the past three years. **RE**

Vital Statistics

Motor: Rear PSM
Battery chemistry: Li-ion
Capacity: 77kWh
Power output: 150kW
Peak charge: 170kW
WLTP range: 410km

GENESIS GV60

Single PSM

The GV60 is Genesis's first crack at an EV. However, Hyundai's premium brand was not starting from scratch thanks to Hyundai/Kia's E-GMP (Electric Modular Global Platform). E-GMP is a decent jumping-off point, due to an 800V power architecture, SiC inverters and neatly integrated EDUs, which, depending on spec, are run on the rear, or front and rear, axles of the GV60.

APTI tested the Premium spec, which means a rear motor with 168kW and 350Nm (the Sport versions get twin motors), providing plenty of punch when needed. Three drive models are available: Eco, Comfort and Sport. Pleasingly, when driven in Eco, the GV60 does not become a sluggish lump – unlike some other vehicles – and nipping out of junctions doesn't lead to any heart-in-mouth moments.

APTI put the GV60 through its paces on a trip from the UK to the Spa Francorchamps circuit in Belgium. It impressed from the outset. The interior quality is exemplary, and Genesis has managed to strike a near-perfect balance between screen-based tech and physical buttons. The combination of a highly adjustable seating position, high-quality materials and an airy feel make for stress-free mile munching. In-cabin noise is minimal and the combination of compliant suspension and 19in wheels on the Premium model (Sports gets 20in wheels) mean the environment is positively cosseting.

The GV60 can accommodate both 400V and 800V charging, with peak power of 350kW. However, when connected to a 350kW charger, the peak charging rate we saw in practice was just over 200kW – still quite respectable. Cruising at freeway speeds takes it toll on range, but at a steady 120km/h, over 300km (without dropping below 10% charge from a 90% starting point) is quite achievable from the 74kWh NMC pack. Over 1,200km of predominantly freeway driving, average consumption was a respectable 5.7km/kWh. Overall, the GV60 is very well executed. With the exception of needing a little more range, it provides everything a driver could ask for in the already crammed SUV segment, with its fit, finish and overall build quality elevating it above more run-of-the-mill competitors. **LB**

Vital Statistics

Motor: Rear PSM
Battery chemistry: Li-ion
Capacity: 74kWh
Power output: 168kW
Peak charge: 350kW
WLTP range: 516km

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Michael Taylor

"Sure, there are plenty of three-letter acronyms in engine work today, but they all, frankly, suck. And could use a hand from a marketing guru"

Proper engineers, especially those who love the oily, spinning bits, look down their noses at marketing people. And rightly so.

Engineers are usually busy searching for the most appropriate formula to maximize the performance of a component, making sure a million of them can be made to fit precisely (even when replaced) and guaranteeing thermal expansion and contraction are within spec.

Marketing people are obsessed with finding the right formula to maximize the performance of an influencer post, spending millions on brand-positioning ads that may or may not even have a car in them, and guaranteeing the thermal accuracy of the Veuve Clicquot refrigerator during team-building weekends in southern France.

That's not to say that the two groups don't see eye to eye. They often do, especially when the other one is not in the same room, on the same day.

There should be a point in every successful engineer's life, though, where they suppress their justified superiority and actually listen to what the marketing people have to say.

There are patterns (and engineers LOVE patterns – or, in engineer-speak, data correlations) that can be of enormous career benefit if used judiciously in the right setting. The foremost of these is the TLA.

There's no point in even sharpening the pencils if the thing you're engineering can't be distilled down into a TLA. It could be the single most beneficial piece of engineering in the history of mankind, but it's dead in the water if you can't describe it in a Three-Letter Acronym.

Even an average car today has ABS, ECU, ACC, CAN, BCM, AWD or FWD, GPS, DSC and ESC. Does it matter if anyone understands them? No. Just keep saying them over and over again and people will eventually believe these things are critical.

Designers figured this out years ago. Even their sometimes ludicrously dreamy design patter has a TLA. Ex-Jaguar design great Ian Callum calls this DBS (Designer Bullshit).

And look at what's happened to designers since they locked on to the TLA strategy. They've become heroes. Their stars have risen as those of the engineers have dwindled to flickering memories – and their permit to usurp you was the TLA. The designers – who like to think they straddle the world between engineering and art – have taken your crown by embracing marketing. And it's not marketing of the car but marketing of their craft.

They began with TLAs then evolved these into their own language, like Tornado lines (because people kept mispronouncing Toronado), kamm tails, bubble roofs and hoods, Hofmeister kinks and tumblehome. You know, stuff that sounds fun and important.

Think back. Until the 1990s, the automotive media was just as fulsome in its praise of names like Colombo, Rosche, Mezger, Costin, Duckworth and Lampredi as it was of designers like Martinengo, Farina, Gandini or Giugiaro. Journalists made engineers legends.

Then came the TLA. Engine gurus have faded into the background in the world's understanding of how cars are made. The engines just kind of are. They exist. They turn up, somehow.

Sure, someone, somewhere kicked things off, but we don't know who it is so we'll let the board member for development talk about it. And did we mention he also looks after design? And how sexy is that infotainment surround and the way we backlit the aluminum cover for the air vent on the dash?

The engine? Well, obviously a development of a thing someone did 20 years ago, but look at how cool the headlight design is in front of it.

Sure, there are plenty of TLAs in engine work today, but they all, frankly, suck. And could use a hand from a marketing guru. I mean, MAF? Just about the most important single piece of a combustion engine and you guys made it sound like a vegetable being eaten by a warthog.

A TPS sounds like a dodgy backstreet tax agency, and who thought to use ICE, when you very clearly should not put it in a gin and tonic?

Then there are TLAs like HEGO, which is actually an FLA, and HO_2S, which breaks a golden rule by sneaking in a number.

No, if you guys want to be great again, you're going to have to put away the pocket protectors, stop looking like Michael Douglas in *Falling Down*, wear a long-sleeved shirt to work sometimes – and befriend a marketer. ⦿

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REE-free

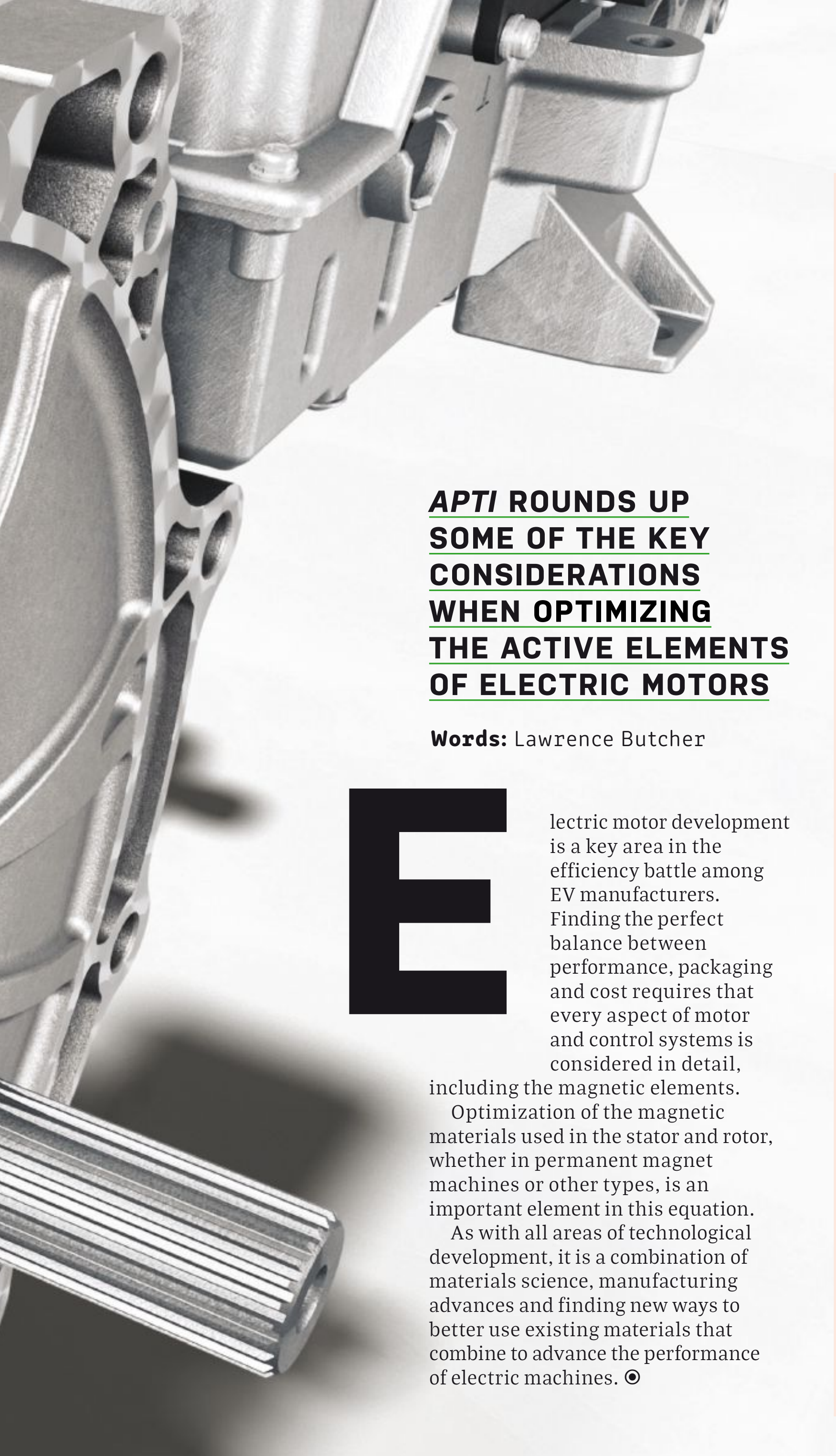
The quest for REE-magnet-free traction motors that match the performance of current PSMs is ongoing. These efforts focus both on using new magnetic materials and improving the performance of existing, magnet-free motor technologies.

Induction motors are commonplace in EV applications, externally excited synchronous machines less so. The former tend to be used in lower-cost vehicles, or as secondary drives, where their lack of zero-load losses means they do not impact overall vehicle efficiency when not being used.

As a rule, induction motors are less efficient than PSMs, meaning for a given output they tend to be larger and heavier. However, recent developments have seen this gap narrow and a number of high-power-density motors have been developed using induction and other principles.

For example, Ricardo's (synchronous reluctance) Alumotor project eliminates not only rare earth magnets but also copper windings (which have been replaced by aluminum). In its initial guise, the Alumotor has no permanent magnets; however, there is the option of using ferrite permanent magnets to create a higher-performance, yet still sustainable version.

PSMs will likely remain the best choice for power density and efficiency for the foreseeable future, but ongoing advances to improve efficiency will see the quantity of magnetic material needed continue to fall.



Magnetic attractions

APTI ROUNDS UP SOME OF THE KEY CONSIDERATIONS WHEN OPTIMIZING THE ACTIVE ELEMENTS OF ELECTRIC MOTORS

Words: Lawrence Butcher

Electric motor development is a key area in the efficiency battle among EV manufacturers. Finding the perfect balance between performance, packaging and cost requires that every aspect of motor and control systems is considered in detail, including the magnetic elements.

Optimization of the magnetic materials used in the stator and rotor, whether in permanent magnet machines or other types, is an important element in this equation.

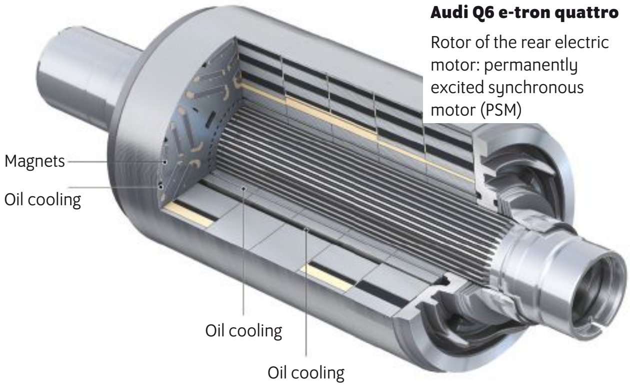
As with all areas of technological development, it is a combination of materials science, manufacturing advances and finding new ways to better use existing materials that combine to advance the performance of electric machines. ◉

Shapes and placement

The type, shape and layout of the magnets in a PSM rotor have a significant effect on overall motor performance.

For example, the traction motors in Audi's Premium Platform Electric (PPE) use three layers of magnets to minimize iron losses. However, the magnets are not of a uniform type throughout the rotor. Instead, in areas with high demands on the magnetic material – such as where eddy currents increase temperatures – higher grades of magnetic material are employed. Where the demands are less severe, lower grades can be used, in turn reducing cost. Furthermore, the three-layer arrangement increases synchronous torque generation by the magnets, and also raises reluctance torque due to an amplification of the reluctance effect by the geometry of the magnet pockets within the rotor.

If dimensional stability of a motor's rotor can be maintained, even at very high speeds, the air gap between the stator and rotor can be reduced, increasing efficiency. However, maintaining a narrow gap presents challenges when surface mount permanent magnets are used as the magnets must be retained. At lower RPMs the magnets can be bonded to the rotor, but for higher-speed use it is often necessary to use some form of retaining sleeve. In high-performance applications, this will often take the form of a composite, filament wound structure.



Audi Q6 e-tron quattro

Rotor of the rear electric motor: permanently excited synchronous motor (PSM)

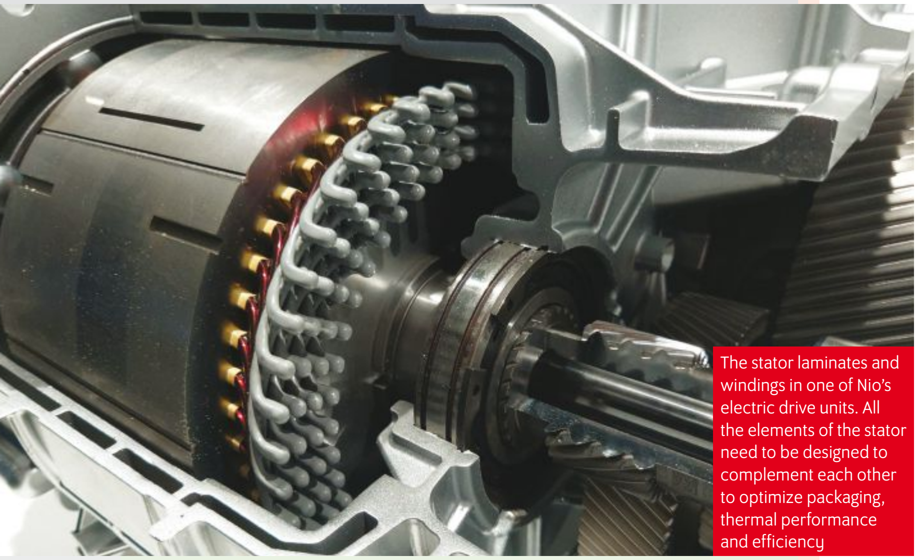
"THE MAIN MATERIALS USED FOR MOTOR LAMINATIONS ARE SILICON STEELS AND IRON-COBALT ALLOYS"

Lamination materials

The two main materials used for motor laminations in traction motors are silicon steel and, in applications that demand higher performance, iron-cobalt or nickel alloys. The materials are chosen due to their ability to support high magnetic flux with high saturation levels and excellent magnetic permeability. Requirements such as electrical resistivity and high thermal conductivity are also desirable, although achieving both in the same material invariably means compromising other properties. For example, the addition of silicon and aluminum alloying elements helps to reduce electrical losses but also reduces thermal conductivity.

One notable recent development in lamination materials is the arrival of amorphous metals, also referred to as non-crystalline metals. The materials themselves have been known about for decades, but it is only in the last few years that developments have made them suitable for use in traction motors.

The non-aligned crystalline structure is highly beneficial for reducing core losses along with exceptionally high magnetic permeability and low hysteresis. However, this structure also comes with disadvantages, mainly due to the manufacturing process, which sees the hot metal cooled rapidly. This gives amorphous metals very desirable properties, but means they must be formed in thin, foil-like sheets, which are very brittle. These cannot be processed in the same way as traditional laminations, but for axial flux motors it has proved feasible to use amorphous metals for stator construction as the stator can be made from a 'coil' of material rather than individual laminates, negating the need for stamping.

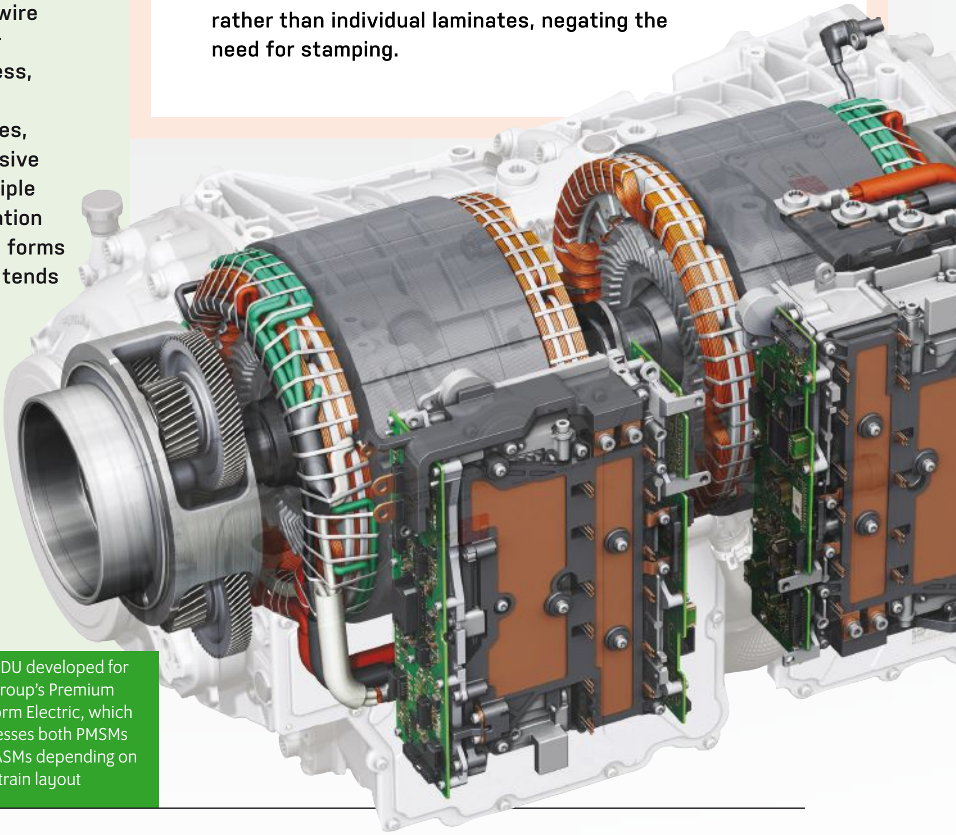

The stator laminates and windings in one of Nio's electric drive units. All the elements of the stator need to be designed to complement each other to optimize packaging, thermal performance and efficiency

Stamping

While for some low-volume and prototype applications, laminates are pre-stacked then cut using either wire EDM or laser cutting, the vast majority of motor laminations are produced using a stamping process, enabling rapid production.

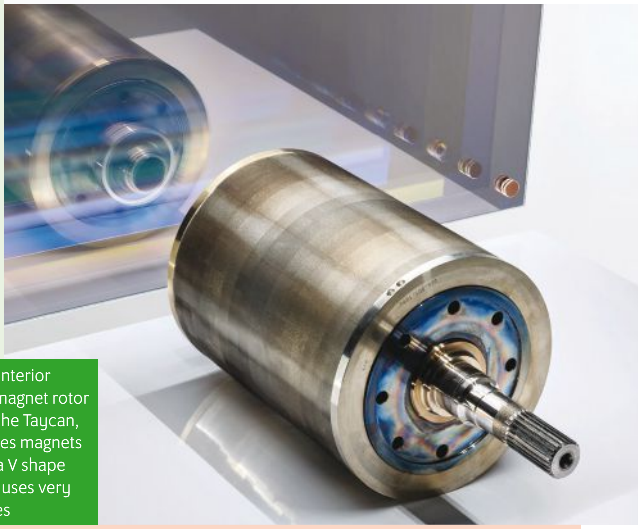
For laminations destined for radial flux machines, there are two main stamping processes: progressive and compound. Progressive stamping uses multiple tools to form the various features of each lamination in a number of stages, while compound stamping forms all the features in a single operation. The former tends to be favored for the production of smaller laminations and the latter for larger items, with both being suitable for mass production of laminates.

For highly complex and thin laminations, such as those used in advanced, high-performance, low-volume motors, chemical etching can be used. This method has a number of benefits, including exceptional accuracy and the absence of a heat-affected zone at the edge of features (as occurs with laser cutting).

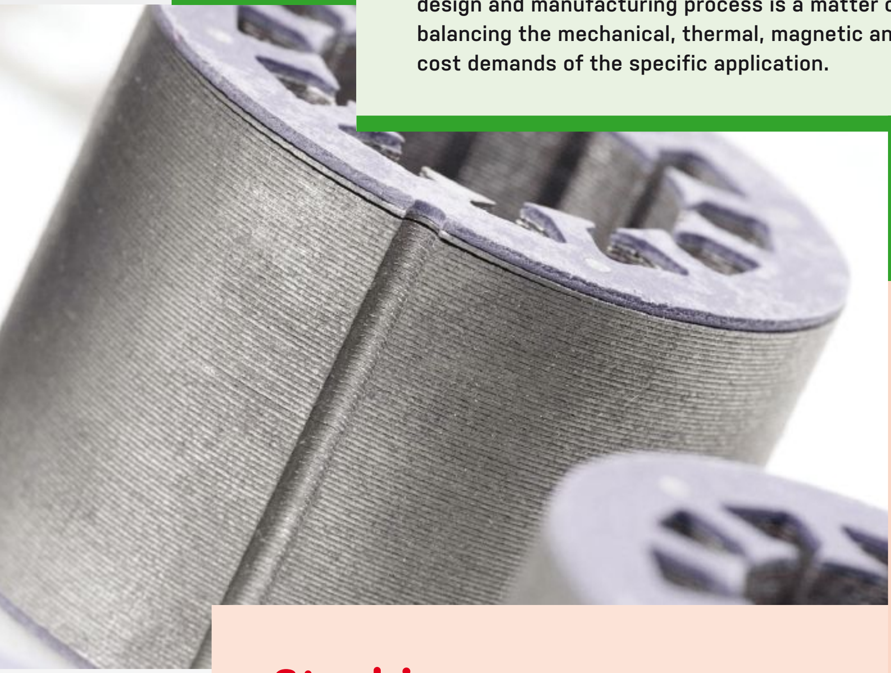

The EDU developed for VW Group's Premium Platform Electric, which harnesses both PMSMs and ASMs depending on drivetrain layout

Laminations

The laminations that make up the motor core, consisting of the stator and rotor, play a significant role in both the magnetic and mechanical performance of a motor. In the case of a permanent magnet machine, the stator lamination stack forms the housing for the windings, while the rotor laminates house the permanent magnets. Selecting the materials, design and manufacturing process is a matter of balancing the mechanical, thermal, magnetic and cost demands of the specific application.



RIGHT: The interior permanent magnet rotor from a Porsche Taycan, which features magnets arranged in a V shape within it and uses very thin laminates



The processing on laminations and the materials used have a significant effect on the performance and cost of electric machines

Stacking

Once cut or stamped, laminations must be bonded together, ideally with each lamination insulated from the next. There are various methods to achieve this, but the most commonly used in EV motors are interlocking/welding and bonding.

Interlocking sees features stamped into each lamination – circular dimples, for example – that mate with the lamination below it in the stack. The advantage of this process is that it can be completed in the same operation as the stamping.

Bonding is becoming an increasingly popular method for joining laminates in EV motors, as it can be used on laminates that are too thin to use interlocking reliably. Of particular interest is the approach of using 'self-bonding' laminates. These are coated on both sides with a temperature-sensitive adhesive prior to stamping (which also acts as an insulator). Once stamped, the laminate stack is heated, activating the adhesive and securely bonding the laminates. Beyond being applicable to thin laminates, a big advantage of this approach is that it ensures integrity between each laminate, maximizing magnetic performance.

Magnet materials

The two most commonly used magnets in PSMs are samarium-cobalt (Sm-Co) and neodymium iron boron (NdFeB), due to their high remanent magnetization and coercive fields (the resistance to opposing magnetic fields).

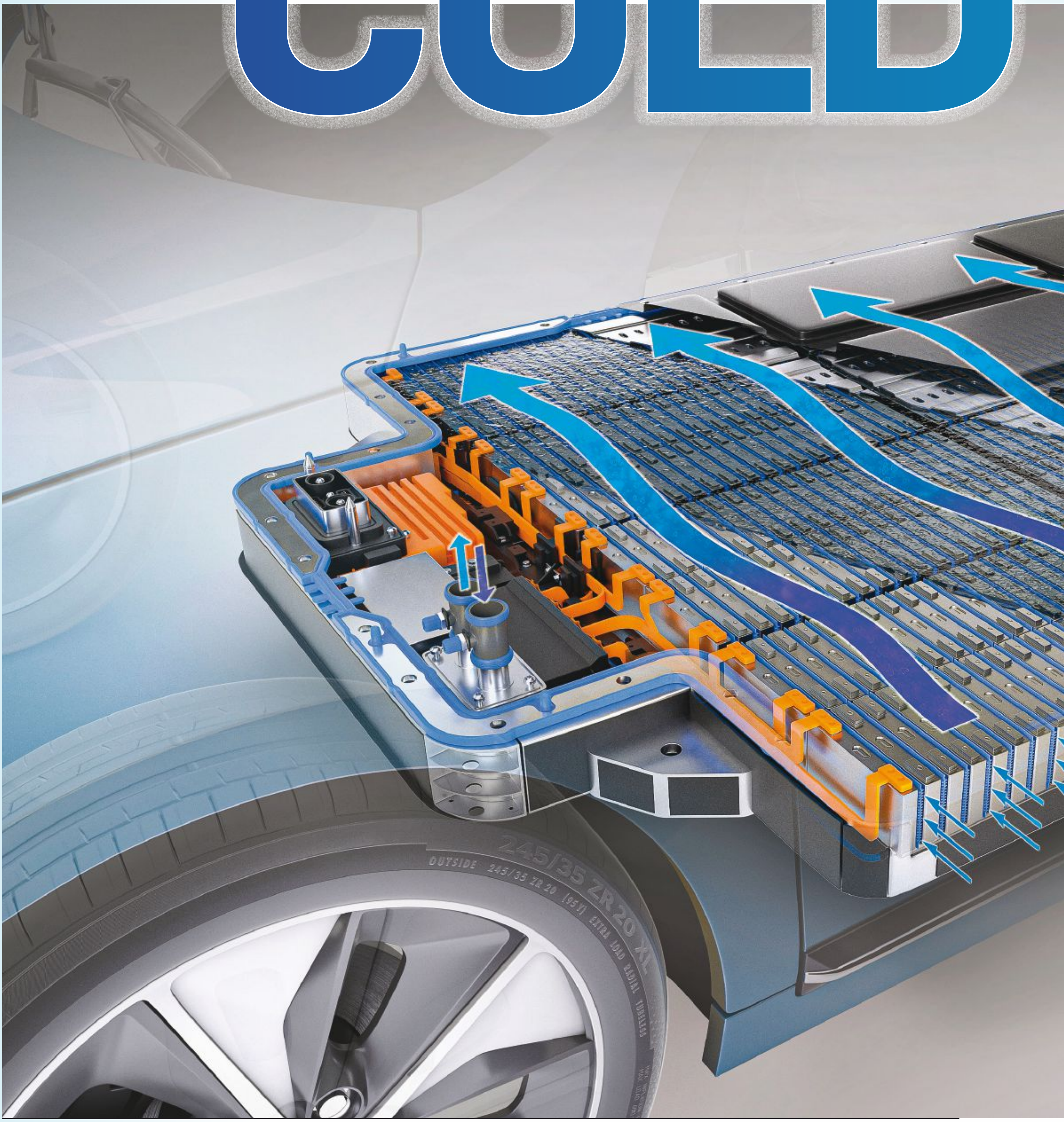
Neodymium is by far the most used, thanks to its exceptional magnetic strength, although its main disadvantage (beyond requiring rare earth elements [REE]) is a relatively low Curie temperature – the temperature at which it loses its magnetism. For this reason, samarium-cobalt, though weaker and more expensive than NdFeB, is a preferred option for use in high-temperature applications. One of the reasons for the focus on cooling in high-performance traction motors is that effective heat removal enables the use of higher-performing neodymium.

Geopolitical and supply chain considerations have given the search for alternatives to REE-reliant magnets new urgency. Ferrite-based magnets are widely available and cheap to produce, but are relatively weak.

However, efforts have been made to maximize their potential. For example, work by Hitachi Metals (now under the brand Proterial) has been undertaken on the topic and demonstrated that steps such as increasing motor speed can bring its ferrite-based motors to performance parity with equivalent neodymium-equipped motors.

Other alternatives under investigation include iron nitride magnets, strontium-ferrite and manganese-aluminum-carbon alloys, though none have yet reached commercial fruition. For the foreseeable future, REE magnets will remain the best option where ultimate power is required. ⦿

COLD


245/35 ZR 20 XL
OUTSIDE 245/35 ZR 20 [95Y] EXTRA LOAD RADIAL TUBELESS

FRONT

IMMERSION COOLING OF BATTERIES IS GROWING IN POPULARITY, DRIVEN PARTLY BY CONSUMER DEMAND FOR EVER-FASTER CHARGING

POTENTIAL HEAT TRANSFER INCREASE OF

10,000x

WITH IMMERSION COOLED CELLS

The online world is awash with polarized debate on many topics. On some quiet news days it seems that chief among these discussions is the subject of electric vehicles. It appears that I am among the group that the more zealous EV advocates would call ‘idiots’ for not immediately succumbing to the clear allure of electric motoring.

Even if I were to ignore the clear environmental advantages of the EV, I am not immune to the other obvious benefits of battery-electric transportation, and I’m an advocate for electric propulsion. Furthermore, the engineering of electrified powertrains has, in one form or another, provided me with around 50% of my engineering-derived income for the past decade and a half. Some of that time was spent thinking about how to keep high-voltage batteries safe from harm while remaining cool in a very harsh environment (Formula 1 motor racing during the early stages of hybrid system use). I won’t go into minute details, but it is sufficient to say that the cutting-edge battery I worked on had a liquid coolant in direct contact with each cell. In this article, this is classed as an immersion cooling system.

For those who haven’t driven an EV, I would encourage you to do so. They really are a revelation. Yes, I can understand the opinion that EVs do not deliver an engaging drive and lack soul and character. However, they are mightily impressive. Quiet, relaxing and with unexpectedly excellent performance for a mundane family car, an EV might surprise you. As someone with a deep interest in engines who has made half a career from working on their design and development, I thought that I would be hard to convince. However, although I will always love engines for many reasons, I believe that EVs will probably become the future for most of us, with or without legislation. They really are that good, even if they are more than a little boring.

“SEALING BECOMES MORE COMPLEX WITH IMMERSION COOLING”

CHARGING DEMANDS

The technical and practical objections to an EV from those yet to make the transition often concern batteries in one way or another. There are perceptions, rightly or wrongly, that batteries take too long to charge, that they degrade, that they don’t work well in winter or that they don’t give the vehicle enough range. If you feel that a vehicle doesn’t have the range you want, who is anyone to argue? If you don’t like the idea of standing at a service area for X minutes or hours while your vehicle charges, that’s a valid feeling. People enjoin us to buy an EV and then stop every two hours for an over-priced coffee and a nutritionally disastrous meal – and many drivers, unsurprisingly, don’t want that from their long journeys. You might be someone who likes to pull up at a fuel pump, spend a couple of minutes taking energy on board, a further two minutes paying and then go straight back out on the road to complete your journey. If an EV manufacturer could provide something close to this, they will would be rewarded with customers.

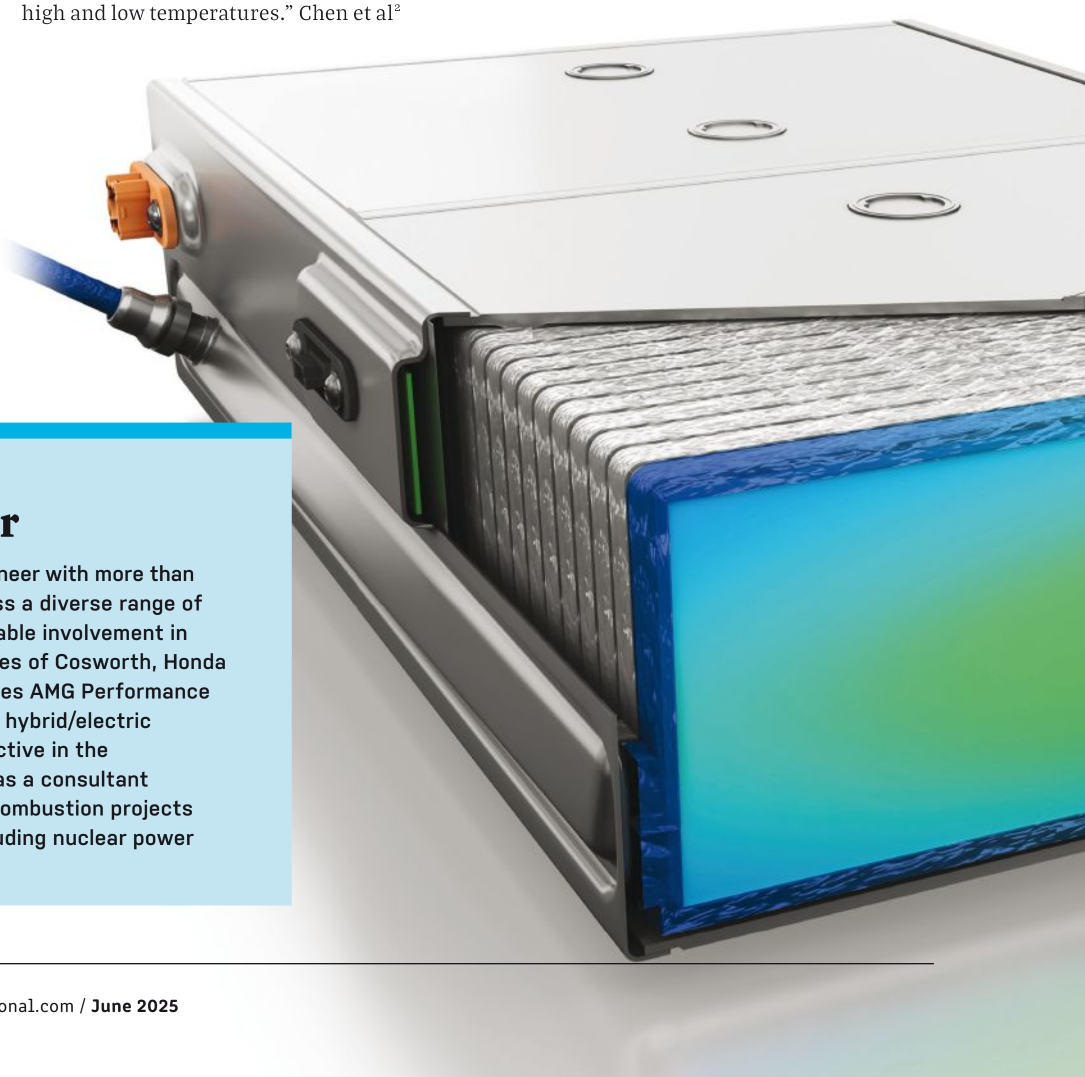
Judging by the number of OEMs producing vehicles with fast-charging capability, this message has been taken on board. By all means, if you enjoy spending long periods of time charging during a journey, feel free to indulge yourself. However, as we shall see, there are large numbers of drivers who want to charge quickly and get back on the road. As you will find in this brief article, such motorists will be pleased that their vehicles have immersion-cooled batteries.

The financial objection to electric motoring is based on the cost of entry, which is significantly influenced by the size and cost of the battery. Many people seem to want a 500km vehicle range. However, the amount of battery required to provide that range costs quite a lot and weighs a surprising amount too. As people also want that same battery to be durable, care needs to be taken with the battery specifications and management during use. In terms of durability, Wahab et al[1] state that, “Battery aging depends on temperature, C-rate and discharge depth. Temperature affects battery capacity most, as aging mechanisms are most pronounced at high and low temperatures.” Chen et al[2] suggest that the optimum range for lithium-ion batteries at the time of their article’s publication was 15-35°C.

Thus, to meet customer expectations of battery longevity, temperature is a primary consideration. Temperature control is achieved through effective cooling and heating as appropriate. In addition, regulatory requirements will enforce minimum levels of vehicle high-voltage battery life, as covered in our article on the impact of the forthcoming Euro 7 regulations (*Set the standard*, March 2024, p24*).

COOLING APPROACHES

It is common to find cooling and heating systems referred to in the literature as battery thermal management systems



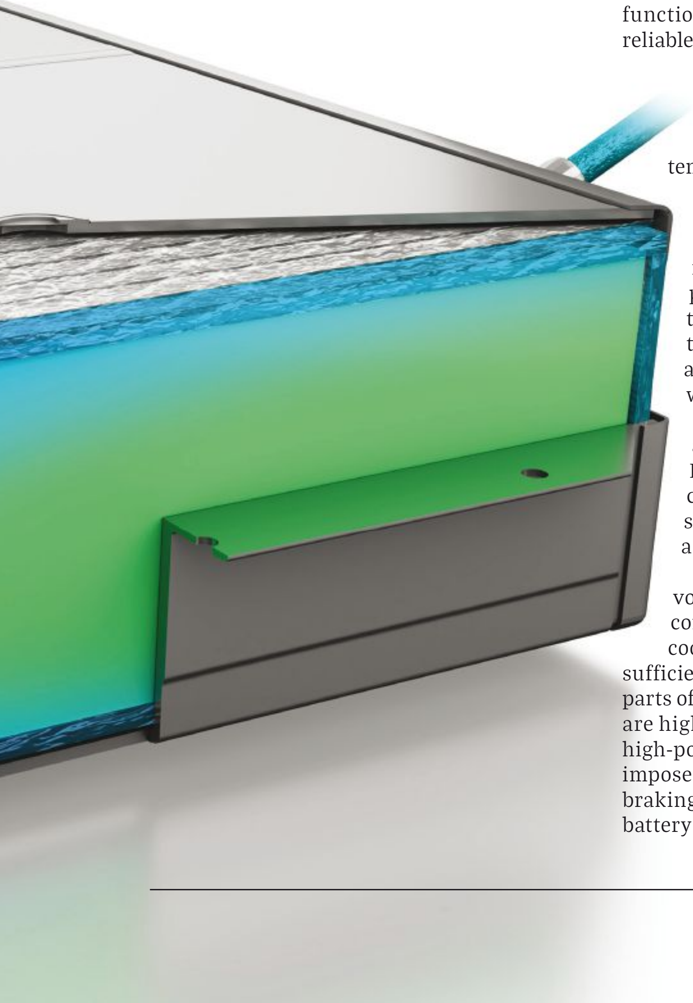
About the author

Wayne Ward is a powertrain engineer with more than two decades of experience across a diverse range of disciplines. He has had considerable involvement in top-level motorsport with the likes of Cosworth, Honda Racing Development and Mercedes AMG Performance Powertrains, working on ICE and hybrid/electric powertrains. He has also been active in the mainstream automotive sphere as a consultant engineer on electrification and combustion projects and across other industries including nuclear power

FAR LEFT: Kreisel offers various immersion cooling ratios for its battery systems

LEFT: Xing Mobility has developed modular immersion-cooled batteries

BELOW: Immersion cooling has the potential to prevent hot spots in packs and create more homogenous temperature distribution



(BTMS), which acknowledges the important function of heating in keeping the battery reliable in the long term.

Performance is also limited by temperature and therefore controlled by cooling and heating. Batteries can perform badly at low temperature and their output is limited at high temperature by both longevity and thermal failure considerations.

Immersion cooling is the term used for batteries that are either fully or partially immersed in a fluid for temperature control. However, the technique of cooling by this method is also effective in heating the battery when required (also known as conditioning). Immersion cooling is also often referred to as direct cooling. Indirect cooling refers to a battery's cells being in partial contact with a solid that is itself directly cooled by a flow of liquid.

For most of the time that a high-voltage battery is operating, thermal considerations are based on keeping it cool enough to be both effective and sufficiently durable. The most demanding parts of the operational cycle for a battery cell are high discharge rates as required by high-power driving, and high charge rates imposed by high regeneration rates during braking and, of course, during high-power battery charging. Recharging batteries can often be the limiting thermal factor on the battery, especially in hot ambient conditions.

As charge rates can be consistently high over a longer period than discharge rates during typical driving (or even during more spirited driving on roads that might encourage sporting driving), cooling performance when the vehicle is charging while stationary is a very important consideration. Hwang et al[3] look at the cooling requirements during charging and say that, "Immersion-cooled BTMS is better suited toward battery packs designed for fast-charging and discharging requirements." Given the present emphasis on increasing charge rates as well as performance, it will therefore be no surprise to find an increasing number of batteries designed with immersion cooling systems.

Air cooling is a commendably simple option for cooling a battery and has been used widely in the past. As Chen et al point out, air-cooled batteries were successfully used for hybrid vehicles such as the Honda Insight and Toyota Prius, but not without temperature excursions significantly in excess of the optimum range, thereby shortening battery life.

As Roe et al[4] point out, "Immersion cooling, which submerges the battery in a dielectric fluid, has the potential of increasing the rate of heat transfer by 10,000 times relative to passive air cooling." Of course, due to the forward motion of any vehicle, the use of passive air cooling is unlikely. However, a vehicle with an overheated battery could find itself at a standstill and unable to reject heat sufficiently rapidly without forced convection. Therefore an 'active' cooling system with a flow of coolant is required. Given the density and specific heat capacity of a liquid coolant compared with air, it is no surprise that heat transfer coefficients are very much higher. However, this improved performance comes with disadvantages, among the foremost of which are increased mass, complexity and cost.

The basic mechanical requirements of such a direct cooling system are a cooling fluid, a pump to vary the flow rate of the coolant through the system, a method of rejecting heat and a method of sealing. If the cell surface is wetted over its whole length, then the sealing arrangement can be relatively simple. If the cell surface is only partially

RIGHT: The construction of immersion-cooled packs is more complex than indirect cooling, but in some applications the benefits they offer outweigh the complications

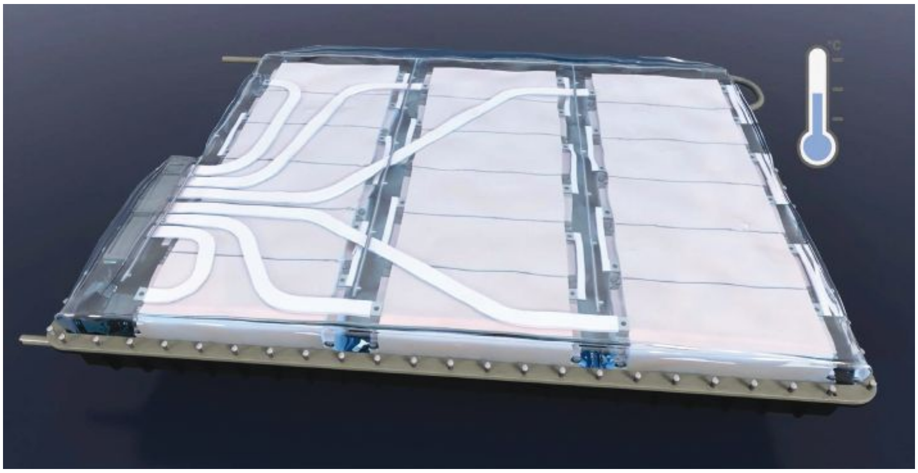
wetted, as per a system described later in this article, then the sealing arrangement becomes more complex with a great number of potential failure points.

PARTIAL IMMERSION COOLING

As the name suggests, partial immersion cooling only immerses a fraction of the cell volume in coolant. Kreisel Electric[5] has patented direct cooling of cylindrical cells with immersion fractions over the range 20% to <100% of the cell's length. This is not a large cavity with a fractional fill volume, but a liquid-filled 'jacket' that extends over the appropriate portion of the cell outer surface. Although perhaps complicated by the requirement to provide two reliable seals against each cell, the reduced bulk and volume of the system should result in a lightweight battery pack. In its patent, Kreisel notes the importance of maintaining individual cell temperature so that the maximum temperature difference does not exceed a certain value. Although it was not dealing with an automotive application, maintaining a large number of individual cells within a tight operating range is something that Electroflight took very seriously in its (non-immersion) cooling system for the battery used in the successful electric air speed record attempt.[6]

TWO-PHASE COOLING

Two-phase immersion cooling takes advantage of the latent heat of vaporization of a coolant. As a fluid reaches boiling point, its temperature remains constant until the phase change is complete. The condensation of the fluid on a cold surface is also a very effective way to reject heat. Hwang et al state, "In terms of EV BTMS applications there are several drawbacks as compared to the single-phase system. Such disadvantage includes gradual loss of coolant fluid due to inefficiencies of the condenser unit, increased system complexity, higher maintenance cost, increased system volume and risk of coolant vapor contamination to the other electronic components at the undercarriage of the EV." They note that this list of disadvantages explains why two-phase systems, although theoretically superior, are less preferred than the conventional (single-phase) type owing to their increased complexity and technical risk.



HEATING

Battery conditioning is undertaken to bring a battery to an efficient working temperature before use. This is important because the battery capacity is much reduced at low temperatures. According to Luo et al,[7] the reduced energy capacity of a lithium-ion battery at excessively low temperatures is "due to the significant reductions in the dielectric conductivity, charge transfer kinetics and solid-state diffusion of lithium ions".

Although it consumes energy to heat the battery, conditioning can be a better use of energy than letting the battery come to temperature through use. It is also a key consideration in battery longevity. If the battery is operated at high charge and discharge rates when very cold, durability will be compromised. Of course, regardless of weather, customers expect to have the full operational performance of their vehicle available, and for durability not to be reduced in order to achieve this. In vehicles with sufficient performance to permanently damage their high-voltage batteries during

> **“IMMERSION COOLING IS SEEN AS A WAY TO PRESERVE LONG-TERM DURABILITY”**

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7) Luo Y, Zhou D, Zou Z, Bi C, Yang X and Li X, ‘An integrated battery thermal management system coupling immersion preheating with immersion cooling’, Omega, Vol 9, Issue 43, October 2024, American Chemical Society, ISSN: 2470-1343

cold-weather operation, those expectations effectively rule out derating vehicle performance or letting the battery come to temperature through use.

SUMMARY

Immersion cooling is becoming increasingly popular with the increase in charge and discharge currents. Single-phase immersion cooling systems with coolant in direct contact with the exterior of each battery cell offer a much more effective cooling method for high-power applications than air cooling, while being less complex than two-phase immersion systems. Indirect cooling is another cooling method that offers comparable cooling performance, but it can be more complex and less efficient. Indirect cooling can also carry a mass penalty compared with immersion cooling. Chen et al provide estimates of the mass added by various cooling methods, with immersion cooling lighter than an indirect system with equivalent cooling performance.

Driven by strong customer desire for ever-faster charging, immersion cooling is seen as a way to preserve the long-term durability of batteries. The trend for fast-charging is applicable to all types of vehicle, irrespective of the actual performance requirements. However sedately and efficiently a driver has covered their 500km (for example) since their last charge, they will expect to add the next amount of charge with the very minimum of delay. Even though they may not have exceeded 100kW discharge during driving, their expectation will be that their vehicle will accept charge at the maximum rate that the charging equipment can supply it. Vehicles that are wanting in terms of charge rates may not sell as rapidly as their makers would like, and a well-designed immersion cooling system is an effective way to ensure that battery longevity remains acceptable. With battery life being a key concern for customers, no OEM wants to develop a reputation for premature battery degradation issues. ◉

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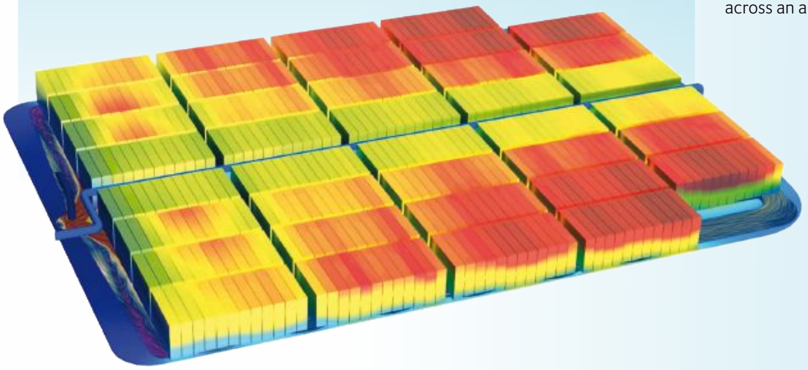
BELOW: A simulation model showing the temperature distribution across an automotive pack



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In-field defects

Graham Heeps

From electronic systems to passive safety, Hyundai's cutting-edge Safety Test & Investigation Laboratory will track down and remedy defects in production cars

Hyundai believes its new Safety Test & Investigation Laboratory (STIL), built

Automotive Testing Technology International
November 2023

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SPECIAL REPORT: Off-highway and commercial

HEAVY METAL

APTI takes a look at powertrain innovations beyond passenger cars

KEEP ON TRUCKING

Commercial fleets are shifting to clean tech

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JOINT EFFORT

Inside the development of a heavy-duty H_2 ICE

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ZeBeyond is accelerating powertrain selection

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iVT EXPO

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iVT EXPO
INDUSTRIAL VEHICLE TECHNOLOGY

HIGHWAY STAR

REDUCING TRUCK EMISSIONS WILL REQUIRE A MULTI-PATHWAY APPROACH, ENCOMPASSING ELECTRIFICATION, SUSTAINABLE LIQUID FUELS AND HYDROGEN

Words: Trinity Francis

SCANIA
SCANIA
SCANIA

LEFT: Scania is one of several heavy-duty truck manufacturers that already have BEVs in production

ANNUAL BATTERY PACK MANUFACTURING CAPACITY

100K

FOR MAN TRUCK AND BUS

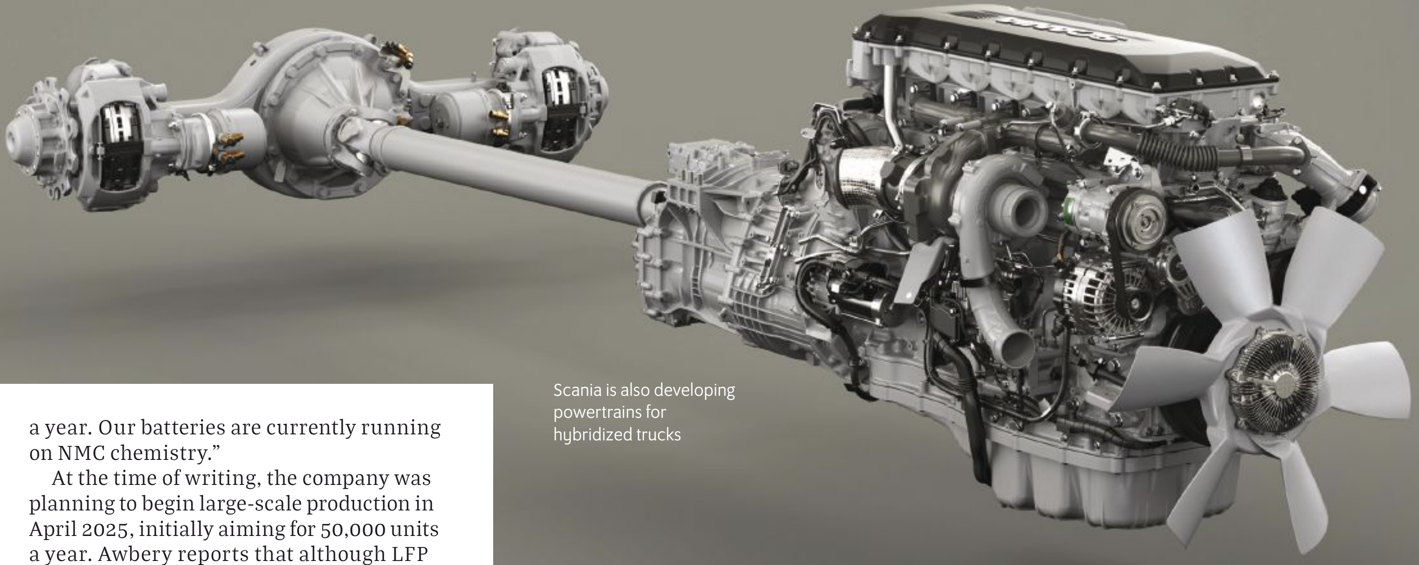
For the heaviest haulage applications, it is commonly believed that there will be no cover-all decarbonization solution. Many truck manufacturers have already launched battery electric versions of existing products, and extensive R&D is underway to optimize these powertrains and develop other low-emission fuels such as hydrogen.

In many ways, legislation is both driving and hindering this phase of HGV decarbonization. Despite looming mandates in many countries, technological limitations render existing legislation inadequate. While it is expected that rules around dimensions, axles and vehicle weights will change, manufacturers must plan for what is legally possible now and hopefully permitted in the future. As Steve Powell, product manager and alternative propulsion lead at Iveco, says, “The legislation has to adapt to cater for a new generation of trucks.”

BEV

BEV trucks are already on the road, albeit in small numbers. In a way that manufacturers never had to consider before, the modularity of e-HGVs is the key to their operational success. MAN, for example, offers up to seven battery packs on one vehicle to accommodate power of up to 623kW and provide 560kW of usable storage.

Ashlea Awbery, product manager at MAN Truck and Bus UK, explains, “Our battery packs are made by MAN in Nuremberg and we have the capacity to build up to 100,000 battery packs



Scania is also developing powertrains for hybridized trucks

a year. Our batteries are currently running on NMC chemistry."

At the time of writing, the company was planning to begin large-scale production in April 2025, initially aiming for 50,000 units a year. Awbery reports that although LFP chemistries are cheaper, MAN prefers the energy density advantages of NMC.

Looking to future battery chemistry strategies, Awbery says, "In a few years' time, we're going to have a joint product in the form of the Traton Modular System, which is a joint platform with Scania as part of the Traton Group. I think the battery cell [chemistry] for those vehicles could potentially change."

At Scania, Jacob Thärnå, director of sustainable transportation, commercial operations, notes, "The majority of R&D investment goes into electrification." The manufacturer's range stretches from urban delivery vehicles up to long-haul HGVs. Thärnå adds, "Scania has designed the battery cell together with our supplier, Northvolt, for heavy-duty purposes.

"During previous generations we learned a lot about how to build battery modules and packs and how we optimize them for charging speeds and life length." Scania's vehicles can now charge at rates up to 350kW with quick progression up to this rate, continuing at this speed until the battery has more than 80% charge and is nearly full.

Despite the potential energy density advantages of NMC, manufacturers such as Iveco and DAF are sticking to LFP. Jurgen De Theije, zero-emission program manager at DAF Trucks, says, "DAF electric trucks come with LFP batteries with a high energy density, which are very advantageous in terms of thermal safety, battery lifetime and the number of charging cycles.

"While solid-state batteries hold great promise, there are still challenges to overcome, including manufacturing scalability, cost and material compatibility. As a consequence, it will take some years before we could consider using these in the heavy-duty vehicle sector."

At this stage, Iveco is focusing its efforts on LFP using Microvast HnCO batteries. Powell says, "We're quite heavily invested in lithium, mainly because that's the established battery chemistry that provides the durability, reliability, availability and cost that make it possible."

E-AXLES

Elsewhere, manufacturers are experimenting with other ways to optimize electric drivetrains. "Our current electric truck generation has a central drive unit rather than an e-axle," says Awbery. "With a central drive unit, we can have a mechanical PTO bolted to it. Also, from a weight distribution point of view, we can keep the weight fairly central." With limits on axle loads, a central drive unit can offer a solution for some of the heaviest applications.

MAN is exploring lighter e-axle solutions for future e-HGV generations but currently favors a central drive unit. Awbery adds, "The way our central drive is currently mounted – with suspended mounts in the chassis – means it's fairly safe from vibration. If you've got an e-axle, the motor and gearbox are subjected to all of the road

RIGHT: Storage space for hydrogen tanks is limited to directly behind the cab and outside the chassis rails on most HD trucks

LEFT: Scania's battery packs can charge at up to 350kW to over 80% SoC

Battery swapping

With differing opinions on the best battery chemistry to use, it seems unlikely that European or US truck manufacturers will implement battery swapping despite its apparent success in China. MAN's Ashlea Awbery says, "There are a lot of benefits to battery swapping but I'm not entirely sure we'll see it in Europe. I believe that's because from a legislative and competitive point of view, it might be quite difficult. It would also mean that we are limited to using the same battery technology, and that can limit innovation."

At Scania Pilot Partner, Tony Sandberg notes, "We have optimized battery installation with a cooling and heating system to preserve the life of the battery. You cannot do that with battery swapping."

> “While solid-state batteries hold great promise, there are still challenges to overcome”
>
> **Jurgen De Theije, DAF Trucks**

Gas options

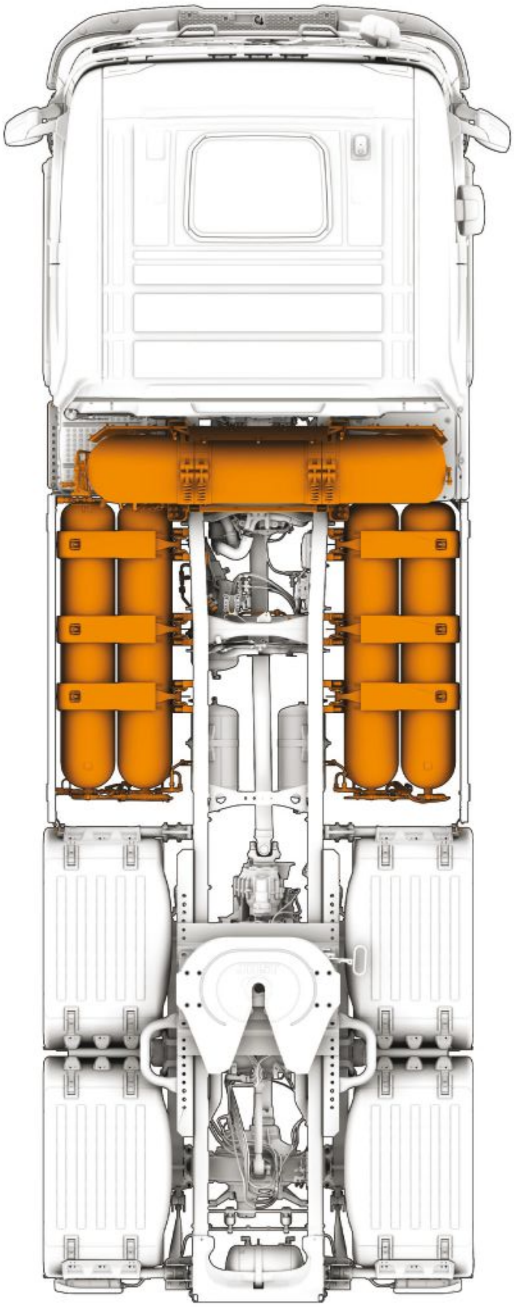
Much of the decarbonization focus is centered around zero-emission fuels, but there are readily available options to reduce road freight emissions now. At Iveco, Steve Powell says, “We've made a commitment as an organization to become carbon neutral by 2040. Our strategy incorporates multiple alternative fuel technologies but it's underpinned by our natural gas product.”

The manufacturer has been selling CNG trucks for more than two decades and LNG trucks for over 10 years. The company's xCursor 13 engine uses a multifuel single base that can be adapted to suit diesel, hydrogen and natural gas. “It was created to futureproof the company's ICE strategy,” Powell says. Iveco's spark ignition gas engine uses a three-way catalyst with a particulate filter in its aftertreatment system.

Similarly, Scania's gas engine utilizes a spark ignition system. Jacob Thärnå explains, “On the gas vehicle we have today, we have a fairly simple catalytic solution because it runs clean enough in the Otto cycle.”

In the short to medium terms, both Thärnå and Powell see gas vehicles, particularly those using biomethane, as a good solution to support heavy-haulage decarbonization since the infrastructure network is more established than alternatives like hydrogen.

Powell adds, “We need to persuade governments to focus more on what we can do right now and how they can facilitate that. And actually getting this net zero journey that they're talking about underway, because at the moment I don't really see that they're doing anything at all.”



vibrations; the only suspension it's got is the tires on the truck.”

Unlike MAN, Iveco has introduced a dual-motor e-axle in the first generation of its largest HGV, the S-eWay. “That's because it offers the best amount of flexibility with chassis space,” explains Powell. He believes that this solution is sufficient to allow ranges of 500-600km. However, any more than that would require legislative changes to permit higher weights or longer truck and trailer combinations on the road.

FCEV

The evolution of regulations is of even greater importance for hydrogen fuel cell electric vehicles (FCEV). Powell says, “A hydrogen tank has to be able to withstand an impact, so you can't store it in the same way. To get any meaningful range from a hydrogen vehicle, [multiple tanks] need to be stacked and the hydrogen stored at 700 bar, so we have to change the way trucks look.”

Most manufacturers are opting to store hydrogen tanks behind the cab. However, smaller, rigid applications have more chassis space to fit hydrogen tanks. At MAN, Awbery explains, “Rather than low in the chassis, the tanks are high behind the cab to keep them safe in the event of crash impacts.” The tanks are fitted with vent valves to allow the gas to dissipate in these scenarios.

Current FCEV development sees MAN's vehicles use around 9kg of hydrogen every 100km. With storage capacity for 56kg, the truck has a range of around 600km. Storing the tanks behind the cab also offers more packaging solutions in the chassis. Despite progression in FCEV testing and development, Awbery says, “We probably wouldn't expect to see an FCEV until about 2030, so they're a little way off yet.”

At Scania, FCEV development is focused on left-hand-drive models due to the position of the air intake on the right side of the vehicle. Tony Sandberg, vice president of Scania Pilot Partner, confirms that to validate the powertrain and roll out limited volumes, the manufacturer will begin with a left-hand-drive configuration before assessing appetite for a right-hand-drive model.

HYDROGEN ICE

At the time of writing, it looks likely that hydrogen ICE in trucking may arrive sooner than FCEVs despite hazy legislative guidance. From a manufacturing perspective, it is far easier to implement, and minimal drivetrain alterations are required. Awbery says, "Our H4576 hydrogen engine is based on our [diesel] D3876 engine and that's available to order now. We're doing a small series run of about 200 vehicles but we can upscale into full production with relative ease if we need to."

The pistons and cylinder heads have been tweaked to work with hydrogen, and spark ignition has been included. The exhaust aftertreatment still uses an AdBlue system. The gearbox and other components remain the same as an equivalent diesel vehicle.

BELOW: Iveco has both BEV and FCEV offerings on the same platform, providing 500km and 800km of range respectively

Similarly, Iveco is using an existing engine as the base for hydrogen ICE development, with its hydrogen Cursor 13 engine undergoing drive cycle testing at the company's research and development center in Arbon, Switzerland.

Awbery anticipates that FCEVs will be preferred in the long term due to better efficiencies. However, she says that heat generation could be beneficial in certain climates. "For instance, Scandinavian countries are looking at hydrogen ICE. We know from BEVs that we put a lot of energy into recycling the heat energy, but when we go into sub-zero climates, we have to create some heat.

"Hydrogen ICE work really well for those environments because the heat isn't wasted and it's used to keep the driver warm." To improve efficiencies across all climates, the company is exploring various heat recovery strategies.

Looking ahead to the future of heavy-haulage decarbonization, Thärnå says, "Europe is moving toward electrification, hopefully very rapidly, but we also see a renewed focus on renewable fuels. There's more investment being put into HVO production capabilities and biomethane."

With any renewable energy source, external infrastructure is a limiting factor. Truck manufacturers are casting a wide net to study several powertrain options but the strength of each will rely, in part, on refueling facilities. Awbery says, "I think specialist applications are going to be looking for hydrogen, as are the countries where the infrastructure for electricity is not there."

De Theije explains that around 400,000 electric trucks need to be deployed across Europe to achieve EU targets by 2030. "To charge the trucks, 42TWh of additional green energy is needed," he notes. "That is the equivalent of the energy consumption of 17 million households – approximately as many households as the UK currently has. To satisfy this additional green energy requirement for commercial vehicles, nine offshore wind farms in the North Sea would be needed, or 11 new nuclear power plants."

Given this projected level of demand, it's likely that multiple fuel options will be needed to support the wider decarbonization of road freight. It stands to reason that along with BEV and hydrogen solutions, governments will need to take a slightly softer approach and legislate for low-emission fuels as well. ⦿

Hybridization

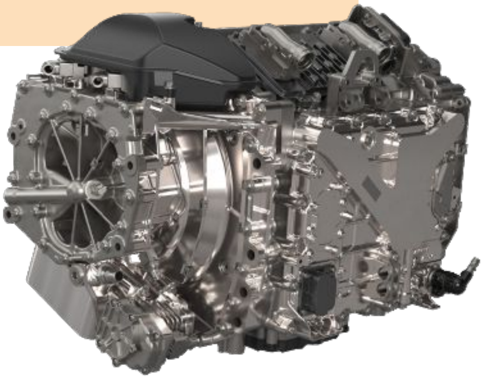
With existing legislation, hybrid solutions fail to fit nicely into a zero-emission category. While some truck manufacturers are doubtful that there is a long-term market for hybrid HGVs, a few are still exploring this technology. At DAF, Jurgen De Theije says, "DAF has successfully been running field tests with hybrid trucks. Hybrids may combine the best of both worlds, using the electric motor in urban areas and the efficient combustion engines outside these areas."

Taking it one step further to create a zero-emission hybrid solution, Iveco's Steve Powell says, "At the moment, steady-state hydrogen ICE work quite nicely. Where that probably works best is as a series hybrid, so an engine driving a generator, a small battery or supercapacitor with an electric drivetrain." Assessing current hydrogen ICE technology, Powell sees this as the best solution.

He continues, "We are developing a series hybrid solution using the Cursor 9 engine." A hybrid setup would allow the truck to be lighter than a BEV and offer more packaging options with a smaller battery. Powell agrees with De Theije that engine use could be geofenced for out-of-town driving, with battery only in residential areas to reduce noise pollution.

Despite the potential benefits, MAN's Ashlea Awbery says, "Because of the way the mandates have worked for the sale of zero-emission-only vehicles, I don't think there's enough time to get huge amounts of development into plug-in hybrid trucks."

> "Europe is moving toward electrification, hopefully very rapidly, but we also see a renewed focus on renewable fuels"
>
> **Ashlea Awbery, MAN Truck and Bus**



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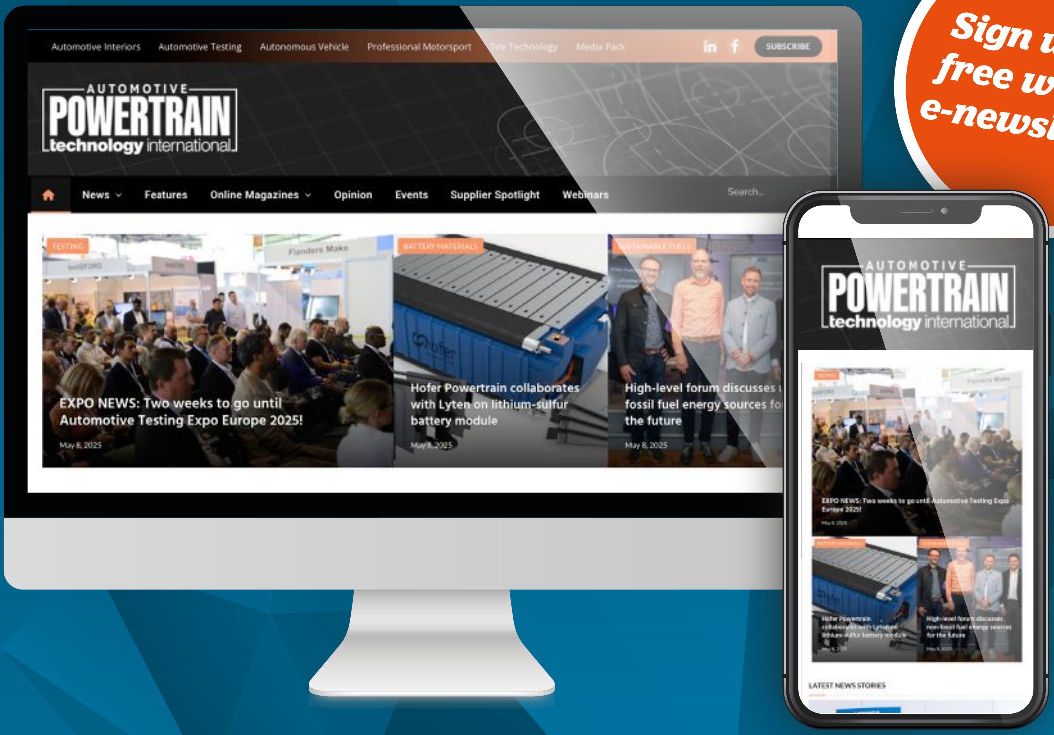

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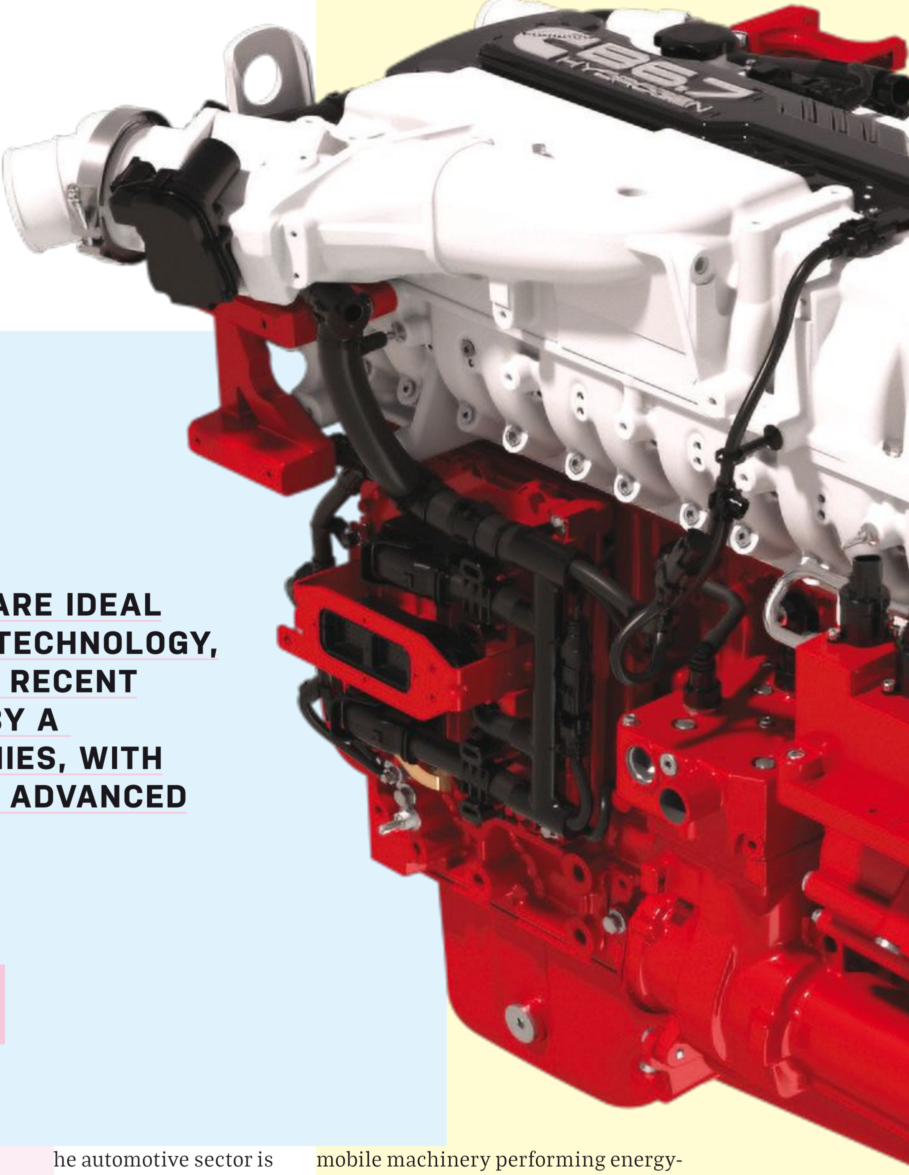


Joint effort

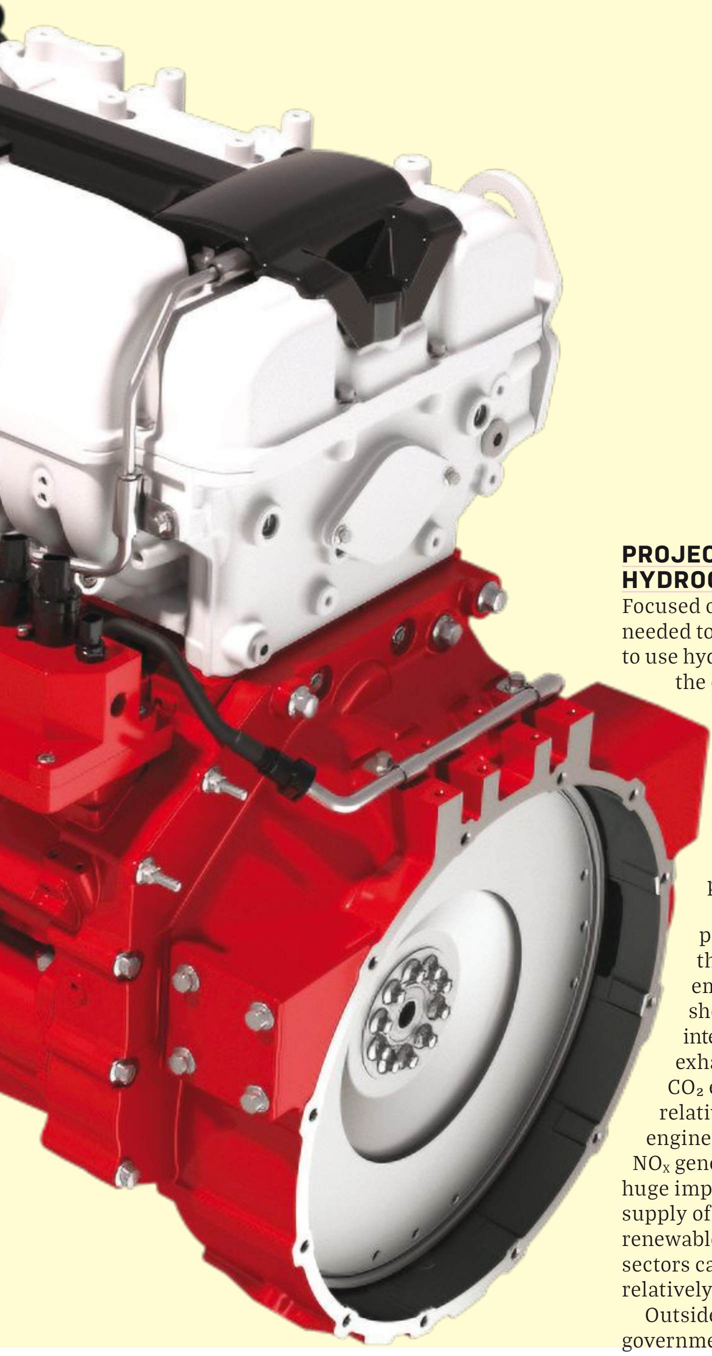
COMMERCIAL VEHICLES ARE IDEAL CANDIDATES FOR H_2 ICE TECHNOLOGY, AS DEMONSTRATED BY A RECENT PROJECT UNDERTAKEN BY A CONSORTIUM OF COMPANIES, WITH BACKING FROM THE UK'S ADVANCED PROPULSION CENTRE

Words: Matt Shillito

The automotive sector is making great progress toward decarbonization in many areas, with 2024 being a record year for registrations of zero-emission vehicles in the UK. Despite this progress, decarbonizing specific heavy-duty applications still poses a challenge when the demands on the vehicles make it difficult to supply energy in the right place, at the right pace, to support their intensive duty cycles. This is where Project Brunel, led by Cummins, believes hydrogen has a part to play as a zero-carbon fuel.

Direct electrification will continue to play a huge role in the decarbonization of all transportation sectors. However, when certain heavy-duty applications cannot be met by existing technology and electric infrastructure, fossil fuels will continue to dominate unless practical zero-carbon alternatives are available. These challenging segments include long-haul HGVs, vehicles with high uptime demands, and non-road mobile machinery performing energy-intensive work such as mining and agriculture. To achieve zero carbon emissions, solutions will be required for all these use cases. This is where green hydrogen, being portable and with higher energy density per kilogram than battery storage is expected to compete.

Using hydrogen in a combustion engine builds on over a century of accumulated knowledge in engine development to deliver a solution that uses familiar components and manufacturing processes, not to mention the significant installed capacity and skills for carrying out these processes in the UK. Hydrogen engines can be readily adapted for existing vehicle architectures and delivered at a lower cost relative to either hydrogen fuel cells or fully electric drivetrains, due to the simpler manufacturing techniques, lower material costs and economies of scale. This established knowledge was well represented in Project Brunel, which was led by Cummins and included Johnson Matthey, Phinia and Zircotec – world leaders in their respective fields of fuel systems, exhaust aftertreatment and protective barrier coatings.



ABOVE: The 6.7-liter H_2-fueled ICE developed by Project Brunel, led by Cummins

LEFT: Matt Shillito is senior project delivery lead at Advanced Propulsion Centre UK

PROJECT BRUNEL – THE EMERGING HYDROGEN ECONOMY

Focused on understanding the changes needed to adapt familiar engine architectures to use hydrogen fuel, Project Brunel proved the concept by running a prototype 6.7-liter engine though real-world durability test cycles in a dedicated test cell. The results were impressive, with the Cummins engine delivering power and torque figures comparable to a diesel, with potential for further improvements.

Alongside demonstrating engine performance and physical durability, the project focused on tailpipe emissions. Data from the project shows that through a combination of intelligent controls and a straightforward exhaust aftertreatment system, tailpipe CO_2 emissions can be reduced by >99% relative to the best-performing diesel engines, with similar large reductions in NO_x generated from combustion. This is a huge improvement and means that with a supply of green hydrogen generated from renewable sources, even difficult heavy-duty sectors can be decarbonized quickly with relatively low up-front cost.

Outside of Project Brunel, the UK government's Department for Energy Security and Net Zero (DESNZ) published an industry-led detailed report in late 2024 capturing inputs from multiple players in the H_2 ICE space. Encouragingly, this showed that the low emissions achieved by Cummins are matched by work carried out by other entities including JCB (see *Hydrogen hopes*, p14) and Volvo – proof that this is a credible route to eliminating harmful emissions in the heavy-duty sectors.

CONSORTIUM APPROACH

While Cummins led the development of the base engine concept, the fuel injection system was developed by Phinia and the exhaust aftertreatment by Johnson Matthey. Oxfordshire-based SME Zircotec developed surface coatings to protect components from the hydrogen environment. Achieving the target levels of durability and combustion stability was no small task, requiring many iterations of simulation and analysis supported by physical testing to arrive at a design that delivered diesel-like levels of performance and efficiency reliably over the long term.

Although the combustion of hydrogen in an engine cylinder is theoretically straightforward, the team initially encountered challenges due to the unique properties of hydrogen gas, particularly when used as a fuel. Hydrogen burns quickly. Combined with the ultra-lean conditions required to minimize emissions, this requires a range of combustion technologies including careful management of injection and spark timing to avoid pre-ignition. The fuel system developed by Phinia required new injector designs and high delivery pressure to achieve stable combustion and meet customer expectations for engine power. In parallel, Zircotec built on its expertise in thermal barrier coatings to create a range of new surface coatings that can serve as a barrier to hydrogen gas permeation, providing options to protect familiar materials and components operating in a hydrogen-rich environment.

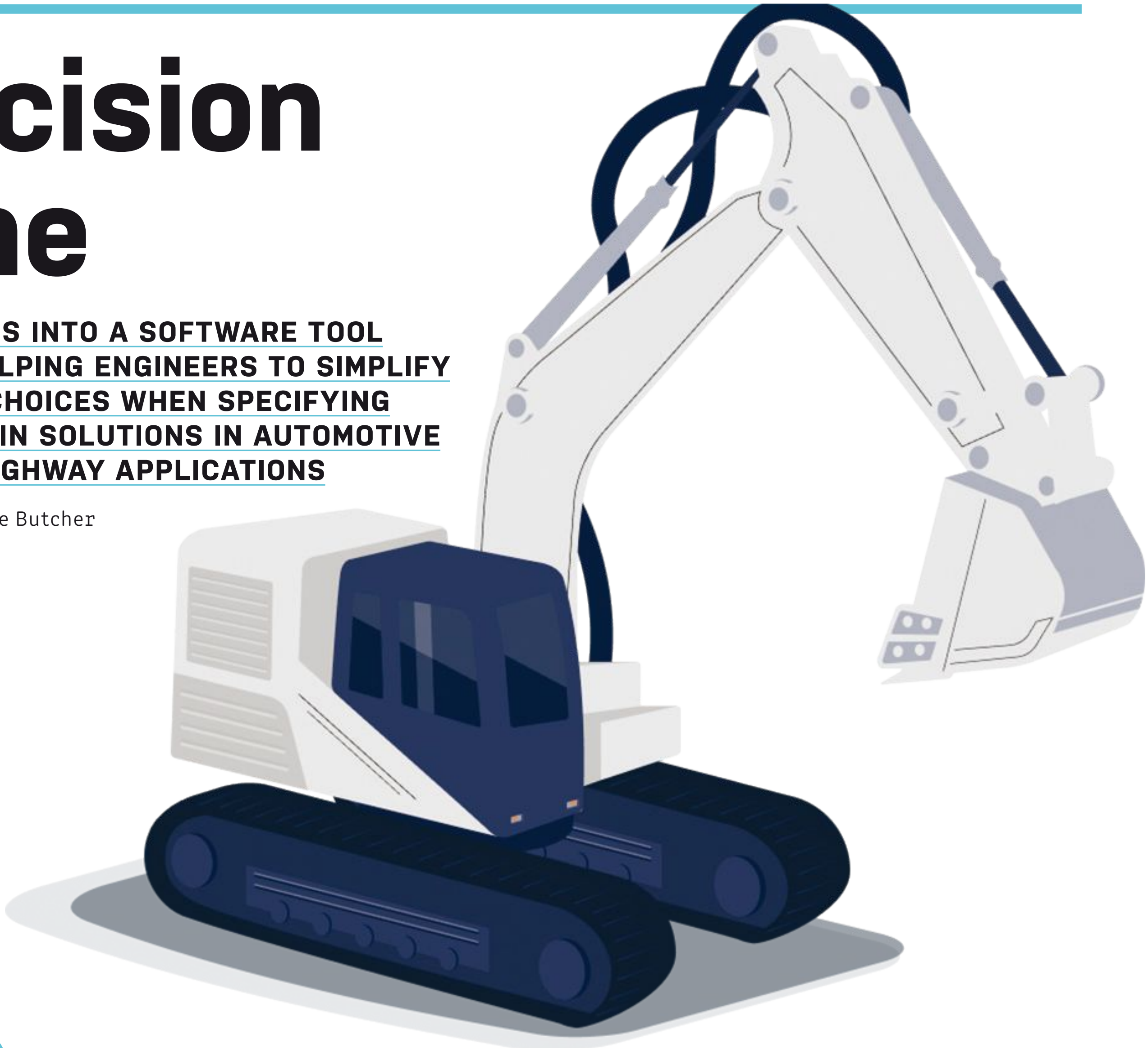
The success of this project and others in the H_2 ICE space shows that the technology is ready to be implemented in real-world fleet trials by early adopters. The fundamental technology is clearly feasible in terms of both performance and durability.

However, questions remain over the readiness of markets to adopt hydrogen as an energy vector, with barriers in the form of legislation around the definition of zero-emission vehicles, rollout of refueling infrastructure and availability of green hydrogen at an affordable price point. Until these barriers can be overcome, the most energy-intensive users in the transportation sector may have one less tool available to help progress toward net zero. ⦿

Decision time

APTI DELVES INTO A SOFTWARE TOOL THAT IS HELPING ENGINEERS TO SIMPLIFY COMPLEX CHOICES WHEN SPECIFYING POWERTRAIN SOLUTIONS IN AUTOMOTIVE AND OFF-HIGHWAY APPLICATIONS

Words: Lawrence Butcher



Being able to quickly find the ideal powertrain solution for a given project is a boon for any manufacturer, be it in automotive or other sectors such as off-highway. Virtual tools have already revolutionized the development process, reducing the number of prototypes required and pushing the need for physical parts further down the line. However, many of the processes used are somewhat disjointed, making it difficult to efficiently find the optimum combination of components from an overall system perspective, taking into account performance as well as factors such as costs and, ever more importantly, sustainability. ZeBeyond, a UK-based software company, is looking to streamline the process and give engineers an all-in-one tool to quickly arrive at the optimum propulsion package for their specific applications.

Over the past five years, ZeBeyond has been honing its ePOP tool in automotive. However, as CTO Bence Falvy explains, the off-highway sector has shown potential for even greater relative gains. “In the automotive industry, high production volumes justify the investment in high-fidelity, multidimensional simulations for each new product iteration,” he says. “These detailed analyses are supported by extensive data availability and standardized load cases.

“In contrast, the off-highway sector operates with significantly lower volumes and far greater application diversity. Here, the lack of accurate load cycle data and the sheer number of possible powertrain configurations often make such detailed analysis impractical (or economically unviable) without better simulation frameworks and data acquisition strategies.”

BELOW: ZeBeyond CTO Bence Falvy

SIMPLIFYING THE COMPLEX

The concept of ePOP is simple, even if its implementation is anything but. The tool enables engineers to input their end requirements for a powertrain and outputs a variety of options for how best to meet those requirements. For example, given a particular drive cycle and package requirement, would an axial or radial flux motor be preferred, or an ASM or PSM? Compared with passenger cars, the level of system complexity in the off-highway market can be very high, but the starting point from an efficiency perspective is often lower, making it possible to achieve impressive improvements over existing solutions.

"Traditional powertrain sizing in the off-highway industry has largely been driven by peak power requirements, with internal combustion engines serving as the default solution," explains Falvy. "However, many of these applications exhibit high peak-to-average power ratios – a characteristic that opens significant opportunities for hybridization or even full electrification, depending on the operational profile. By matching energy sources more intelligently to the actual demand patterns, it's possible to achieve substantial gains in efficiency.

"Designing and sizing hybrid powertrains is inherently complex, as it extends beyond traditional power-based considerations to include energy management and time-domain dynamics. This multidimensional design challenge requires advanced tools and methodologies. The off-highway industry has a unique opportunity to accelerate hybrid system integration by adopting best practices from the automotive sector, where high-dimensional analysis techniques have matured over years of intensive development and high-volume deployment."

COST WINNER

While efficiency is an important selling point in automotive, total cost of ownership (TCO) is king in the off-highway and commercial vehicle arena. Because ZeBeyond's tools encompass the entire product lifecycle, they offer the opportunity to dramatically affect this metric.

It is this aspect that has enthused CEO Wiktor Dotter. "That's where I'm so excited about off-highway," he says. "With passenger cars, you're not selling to a fleet, you're selling to households. If you're selling to a fleet and you can deliver improved efficiency, you're saving dollars, you're saving gallons of fuel and you're selling uptime. If you can size a portfolio of machines to a mine, and say, 'Okay, it is five times the cost per component, but you will double your uptime,' it's a no-brainer."

Central to these potential improvements is a proper understanding of the end use environment for the powertrain, be it an excavator or even a stationary generator unit. "In hybrid powertrains, the optimal balance between battery capacity, internal combustion engine size and electric motor power is critical to maximizing energy savings," says Falvy. "When correctly sized and integrated, these systems can significantly reduce fuel consumption and operating costs, directly contributing to a lower total cost of ownership."

Notably, ZeBeyond's off-highway toolset allows not only for the main powertrain to be defined and refined but also for the myriad auxiliary drives, such as hydraulics, to be optimized. "You could be talking about a hydraulic load, or a fan that needs to run for a cooling system," highlights Falvy. "You can end up with a large list of various power types, hydraulic, electric, mechanical, rotational and so on. Compared with the automotive solution, where we are just looking to drive the wheels, in the off-highway industry, while the fidelity of the individual components is reduced, the fidelity and complexity of the overall solution explodes. You have a very large number of options to consider, and we are developing various ways of addressing that, allowing customers to understand the hundreds or even thousands of options available, ascertain which is best and arrive at a package with the best TCO, or the lightest solution, of any other KPI they choose."

BUILDING BLOCKS

ZeBeyond tends to work with system integrators and engineers to ascertain their high-level requirements for a particular project. These are then used to create measurable output metrics, such as power requirement versus time. Unlike automotive, where there are already established test cycles such as WLTP, very few such cycles exist in off-highway, particularly where a piece of plant may be produced in very low numbers or even be unique. In such cases, Falvy says the company will work with clients to establish baseline use cycles from scratch, with the tool enabling users to create individual cycles across a workday for each power output requirement.

ZeBeyond is constantly working to broaden the data to which its tools have access. "We are collaborating with suppliers of components, for example internal combustion engines and battery suppliers, and integrating their catalogs into our tool," notes Falvy. "From there, we can go into the real world and say, 'Okay, I know you would like a 25kW ICE engine, for example, but you may only have a 30kW and 20kW available.' We can then ask the tool which of those would be the best pick as it is possible one will be better than another."

With relentless pressure on development timelines and industry-wide hesitation to commit to major electrification projects, manufacturers are increasingly seeing ZeBeyond's software as essential. By drastically lowering barriers through software simulation, its tools quickly reveal where electrification makes business sense and where it doesn't, enabling faster decisions and freeing resources to refine final products aligned closely with customer needs. ⦿

ZeBeyond
To find out more, scan the QR code or visit:
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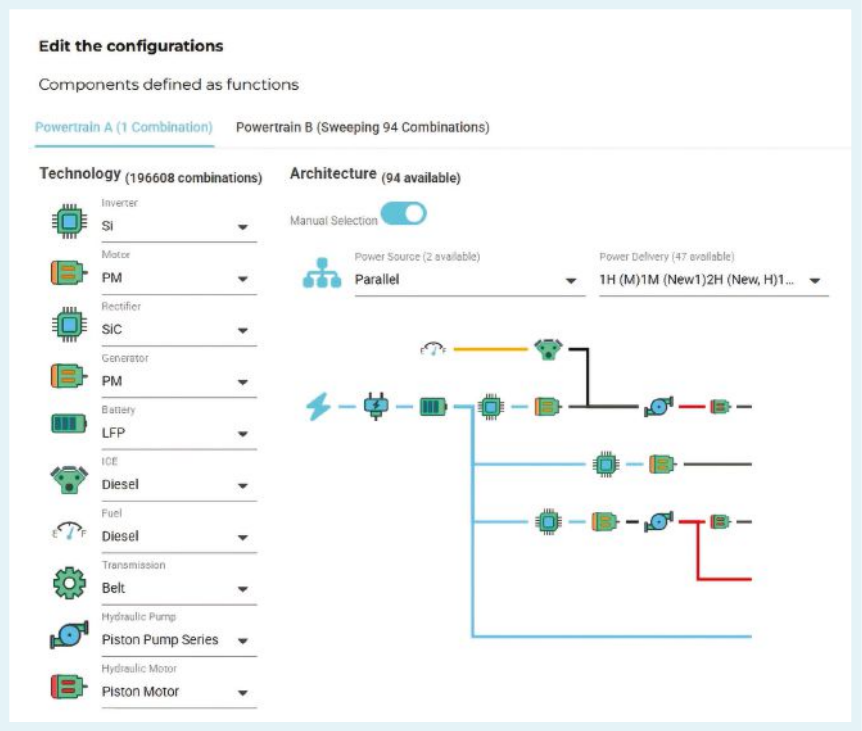
BELOW: ZeBeyond's software provides an intuitive interface that enables the rapid comparison of different powertrain configurations



Edit the configurations

Components defined as functions

Powertrain A (1 Combination)
Powertrain B (Sweeping 94 Combinations)

Technology (196608 combinations)

Inverter: Si
Motor: PM
Rectifier: SiC
Generator: PM
Battery: LFP
ICE: Diesel
Fuel: Diesel
Transmission: Belt
Hydraulic Pump: Piston Pump Series
Hydraulic Motor: Piston Motor

Architecture (94 available)

Manual Selection

Power Source (2 available): Parallel
Power Delivery (47 available): 1H (M)1M (New1)2H (New, H)1...

HEAVY-DUTY POWER

Discover the latest off-highway powertrains

The world of heavy-duty and off-highway propulsion is subject to the same pressures as automotive when it comes to decarbonization. The industry is teeming with innovative powertrain solutions designed to withstand the harshest conditions, and many of them will be on display at iVT Expo at Köln Messe, Germany, June 11-12, 2025.

iVT Expo is *the* destination for those involved in the development, deployment and adoption of industrial vehicle technologies. Bringing together leading suppliers and cutting-edge innovators, the event showcases next-gen components, systems and tech revolutionizing the future of industrial vehicles. Read on for a snapshot of what the event has to offer...

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INDUSTRIAL VEHICLE TECHNOLOGY
JUNE 11 & 12, 2025
KÖLN MESSE, GERMANY

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Summit highlights*

How to optimize powertrain efficiency with cost-competitive IGBT

Mikel Peral, CEO, NX Technologies
The presentation will explore the current challenges and advances in electric mobility, focusing on motor controller efficiency. It will evaluate the role of silicon carbide (SiC) technology in optimizing motor controller performance, particularly in electric vehicles (EVs). The discussion will include benchmarks of EV efficiency, energy loss analysis and comparisons between SiC- and IGBT-based inverters. NX Technologies will introduce its proprietary VarioSwitch motor control software as a competitive alternative, achieving SiC-like efficiency improvements with IGBT inverters with no extra hardware cost for the vehicle.

Opportunities for off-highway decarbonization

Philippa Oldham, stakeholder engagement director, Advanced Propulsion Centre UK
What role can hydrogen play in the decarbonization of off-highway vehicles? Hear about some of the case studies funded in the UK through the Advanced Propulsion Centre, along with insights into the technology development and supply chain opportunities. This will include examples of businesses that are making the transition, challenges in the supply chain and future trajectory for technologies such as H_2 storage, FCEVs and H_2 ICE.

The flexible use of renewable fuels in non-road applications

Paul Moore, technical engineering manager, Caterpillar
For off-highway, the CO_2 reduction legislative roadmap is neither defined nor yet proposed. Looking to non-road mobile machinery (NRMM), the demands for power density, integration, range, robustness, up-time and package space all indicate the future need for energy-dense fuels. These demands offer potential for a more holistic approach, including renewable fuels. Besides hydrogen, sustainable fuels such as alcohols, renewable natural gas and paraffinic fuels could be explored. Caterpillar will give an overview covering the future drivers, needs and boundaries of the NRMM sector. The possibilities of adapting existing powertrains for alternative fuels will be presented and discussed.

Book your delegate pass here
*Rates apply

NX Technologies

High-voltage inverter and BMS portfolio for off-road applications

NX Technologies offers a complete portfolio of inverters and BMS for any off-road application. During iVT Expo, the company will present several products that will benefit off-road and heavy-duty vehicle OEMs and integrators and significantly improve system performance, integration, cost and efficiency.

The BMS offers up to 1,000V, an 18s cell monitoring unit, pyro fuses and eight-contactor control. It is ISO 26262 ASIL D certified and CybSec ready for ISO 21434 microcontrollers.

The R300 inverter covers powertrain systems from 800V to 1,200V, from 250kW up to 400kW peak, with a size of less than 7 liters. The 040 inverters cover high-voltage, low-power auxiliary systems up to 60kW peak with a footprint of just 2.5 liters and 2kg. Upgraded versions of existing E150 and W90 inverters cover a wide range of 400V and 800V applications from 60-210kW with a power density of + 35kW/kg.

NX Technologies has partnered with leading OEMs and Tier 1 suppliers across Europe, North America and Asia. Committed to industry-leading standards such as ISO 26262, it helps customers reduce time-to-market and NRE project costs, and build competitive electric vehicles.

BOOTH: 1030

Trailer Dynamics

Innovative e-trailer drive system

Trailer Dynamics will present the latest generation of its electric drive axle for e-trailers at iVT Expo. The integrated e-axle comprises a drive system with powerful decoupled motors and central gearbox, innovative functional control arm/axle bridge combination, inverters and an e-trailer-specific PDU (power distribution unit).

Particularly noteworthy is the seamless connection to the battery system, which enables efficient energy use, maximum range increase and optimized driving dynamics. Thanks to intelligent control and precise power regulation, the e-axle significantly increases the efficiency and economy of electrified commercial vehicles.

With this solution, Trailer Dynamics sets new standards in the decarbonization of logistics, and offers trailer manufacturers a cost-efficient e-trailer drive solution from a single source. Visit the booth and experience the future of e-trailer technology up close and virtually.

BOOTH: 2045

DUROT
electric

Heinzmann

Customizable PRI motor series

Heinzmann, a leader in electric drive technology, will debut its new PRI motor series at the expo.

The PRI series features compact, high-performance synchronous motors with interior permanent magnet (IPM) rotor technology. Designed for mobile and stationary applications, these motors offer customization options for seamless integration into various systems.

Crafted from high-quality aluminum alloy, the motors ensure mechanical robustness, corrosion resistance and a high degree of protection, making them ideal for demanding conditions.

Their key features include high torque and efficiency; maintenance-free, air-cooled design; reduced magnetic material for cost-efficiency; modular architecture and energy recuperation; custom applications shaft options and electromechanical brake compatibility; and versatile construction.

Ideal for e-mobility, agriculture, municipal machinery, industrial applications and hydraulic systems, the PRI series sets new standards in innovative, reliable and cost-effective electric drive solutions.

Heinzmann continues to drive technological excellence, offering adaptable motors for diverse industries.

BOOTH: 2060

Qexpand

Precision control for high-performance electric vehicles

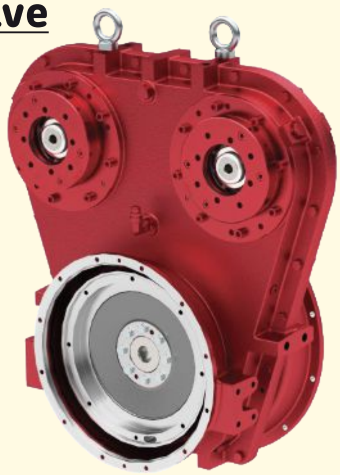
On display at the expo, the LPM80S35DJ004-300 permanent magnet synchronous integrated motor controller is a high-performance vector controller designed for driving permanent magnet synchronous motors. It is suitable for use in AGVs, electric forklifts, electric tow tractors, boom lifts and other vehicle types.

By adopting advanced vector control algorithms, it achieves precise control of motor speed and torque, meeting the operational requirements of vehicle traction. Through a series of motor load and onboard operational tests, the controller ensures motor stability and reliability. It incorporates multiple protection mechanisms to enhance user safety, and the software can be customized according to the user's specific working conditions.

BOOTH: 5220

Twin Disc

Heavy-duty AM080 rear engine power take-off drive



Twin Disc's AM080 rear engine power take-off (REPTO) drive with MasterClutch delivers enhanced horsepower for demanding applications. The MasterClutch technology enables power generation via power take-off (PTO) or power take-in (PTI) in forward, neutral and reverse. With a 700hp maximum power rating at 2,600rpm, it drives hydraulic pumps, grinders, crushers, dredgers, chippers, shredders and drills.

A standout feature of the AM080 is its high-power capacity, with each pump tower supporting up to 400hp and a combined 450hp for dual towers. Its rotatable design (0°, 45°, 90°, 180°) and interchangeable pads and splines allow seamless adaptation to various installations.

Available in single- and dual-tower models, the AM080 offers pump tower ratios of 1.00:1, 0.87:1 and 0.77:1, up to four pump pads and maximum input torque based on theoretically unlimited gear life and a minimum L10 bearing life of 10,000 hours. Designed for severe-duty performance, the REPTO integrates seamlessly with Twin Disc's industry-leading power transmission solutions. It complements a system of Twin Disc products that work together, including power take-offs, marine gears and transmissions. Find out more at the expo.

BOOTH: 4200

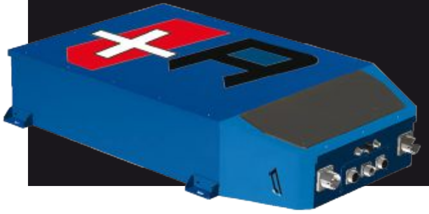
Aliant Battery

Solid-state lithium battery for heavy-duty applications

Aliant Battery, a brand of lithium batteries by Elsa Solutions, has launched a revolutionary solid-state lithium battery. This cutting-edge technology is set to transform energy storage solutions, especially for heavy-duty applications, offering significant improvements in volumetric and gravimetric energy density, as well as enhanced safety features.

Despite technological advances, Li-ion batteries remain susceptible to thermal runaway. However, solid-state lithium batteries offer a safer alternative due to their unique composition and design, making them immune to thermal runaway. This critical safety advantage makes them ideal for high-risk applications.

The state-of-the-art Aliant solid-state lithium battery, referred to as the SSC Battery, features a scalable module of 56V/246Ah/approximately 14kWh. Engineered with innovative technology, these batteries ensure maximum robustness and safety, setting a new standard for high-power stationary energy storage and marine applications. Encased in an automotive-derived aluminum shell, they achieve energy density levels of approximately 220Wh/kg and around 250Wh/l at the battery pack level. Aliant Battery's proprietary battery management system, Pegasus BMS, and multiple quality checks at every production stage highlight the Italian brand's high standards. Specifically designed for special propulsion systems, these batteries support full electric and hybrid propulsion, offering maximum efficiency and a high protection level (IP65). Learn more at iVT Expo.



BOOTH: 1005

Danfoss

Drive performance, efficiency and innovation

Visit Danfoss Power Solutions at iVT Expo to discover its latest advances in mobile hydraulics, electrification and autonomous solutions, all designed to elevate machine performance, boost efficiency and drive innovation.

Danfoss is helping OEMs modernize machines for improved operator experience. Its portfolio includes ergonomic remote controls in the Ikontrol family, JS1-H joysticks and updated user interfaces on its DM display series.

With Danfoss autonomy solutions, OEMs can amplify machine and operator productivity. The company designs autonomous and semi-autonomous systems for off-highway machines. Visit the Danfoss booth to see the company's software, engineering services and the latest solutions within the Plus+1 Autonomous Control Library.

Danfoss Editron offers electric and hybrid powertrain systems for heavy-duty and commercial vehicles and machines on land and sea. The company designs, manufactures and delivers sophisticated hybrid and fully electric drivetrains that cut fuel and energy consumption, reduce carbon dioxide and small particle emissions and can be easily integrated into various types of machines.

BOOTH: 2000

Kiepe Electric

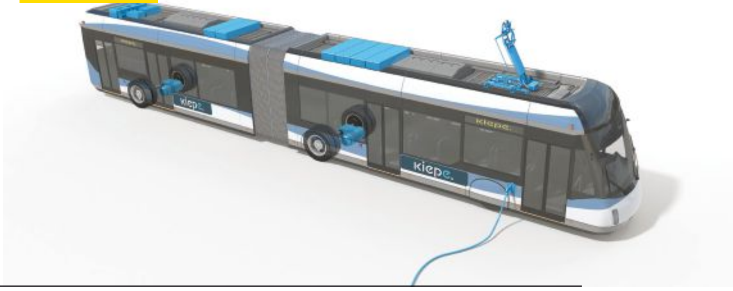
Powertrain solutions for 24/7 operations for special electric vehicles

Kiepe Electric will showcase its advanced powertrain and charging solutions at the expo in Cologne. With extensive experience in the public transportation sector, Kiepe Electric offers integrated solutions for industries such as mining, marine, agriculture and logistics. The company's High-Power Charging (HPC) technology supports up to 800kW, and its In Motion Charging (IMC) technology ensures continuous operation.

Kiepe Electric will also launch the KTI 3xx traction converter, a functionally safe automotive component, at the exhibition.

Committed to the highest safety standards, the company provides reliable and efficient solutions for heavy-duty applications.

BOOTH: 6060



Pulsgetriebe Gear Systems

Customized gear solutions for industrial vehicles

Pulsgetriebe will showcase its innovative gear systems at the expo in Cologne. As a specialist in customized gear solutions, the company prides itself on delivering products that are tailored to meet the unique needs of customers. With its 'first-time-right' approach, it ensures flawless performance right from the start.

Pulsgetriebe's focus on seamless integration of electric motors makes its systems an ideal choice for the rapidly growing e-mobility sector. Designed with a compact structure, the company's solutions maintain high speed and exceptional efficiency without compromising on performance. Whether for electric vehicles or industrial applications, Pulsgetriebe's gear systems provide reliable, efficient power transmission.

BOOTH: 8080

Ecovolta

Next-gen battery system

Ecovolta's in-house research and development team has designed a groundbreaking battery solution set to debut in a vehicle developed by Viktor Meili. This advanced battery, equipped with integrated cooling, uses next-generation lithium-ion cells, setting new standards for capacity and efficiency.

The vehicle is engineered for year-round operation in extremely confined spaces. With the integration of the new battery system, it will be capable of completing an entire workday without requiring a recharge, even while simultaneously powering auxiliary equipment such as plows, spreaders and pressure washers.

The lithium-ion battery consists of two units connected in series, delivering a total capacity of 72kWh at 400V, with each unit providing 36kWh. The compact design boasts impressive energy density. Active cooling ensures that the battery can be recharged in under two hours without overheating. The cooling system uses the vehicle's air-conditioning compressor, which is more efficient than traditional methods.

Once fully integrated, the battery will undergo extensive testing and certification. This battery type will later be added to Ecovolta's product portfolio, featuring customizable cooling housings tailored for the specific demands of off-highway.

BOOTH: 4080

Epec

Next-generation power distribution units for electrified off-highway vehicles

Epec, a provider of intelligent control systems and electrification solutions, will feature its latest power distribution units (PDUs) at the expo. The two new PDUs – Epec Flow Mini PDU and Epec Flow MCS PDU – are designed to enhance the efficiency, safety and scalability of electrified off-highway and commercial vehicle applications.

The Epec Flow Mini PDU is a compact, high-performance distribution unit for high- and low-voltage applications. It is ideal for auxiliary and low-current distribution needs, ensuring seamless integration with key components like motors and batteries. With a continuous current capacity of 300A, the Mini PDU offers a robust and space-saving solution for various vehicle architectures.

For megawatt charging applications, the Epec Flow MCS PDU provides an advanced power distribution solution. It includes an integrated charging controller compliant with ISO 18115 (CCS/MCS DC charging), actively optimizing current flow. With a maximum charging capacity of 1,000A at 1,000V DC and peak current handling of 1,500A, it ensures reliable and high-efficiency energy transfer for next-generation electrified machinery.

Both PDUs are built for demanding environments, with IP6K9K/IP67 protection ratings ensuring durability and reliability.

BOOTH: 2090

EVR Motors

High-power and high-torque-density electric motors for industrial applications

EVR Motors will showcase its advances in electric motor technology at the expo, highlighting the next evolution of its proprietary Trapezoidal Stator Radial Flux Permanent Magnet (TS-RFPM) technology. The company's innovative motor design integrates 3D trapezoidal teeth and pre-wound 3D coils, maximizing magnetic flux generation and copper use. The modular architecture allows for seamless adaptation to diverse voltage, speed and power requirements, ensuring high power and torque densities across multiple industrial applications.

Building on its commitment to customer-centric solutions, EVR Motors has enhanced customization capabilities, offering tailored motor configurations for industrial OEMs. These developments reinforce long-term collaboration by enabling flexible, high-performance industrial motor solutions that meet the evolving needs of the electric industrial mobility sector.

BOOTH: 4150

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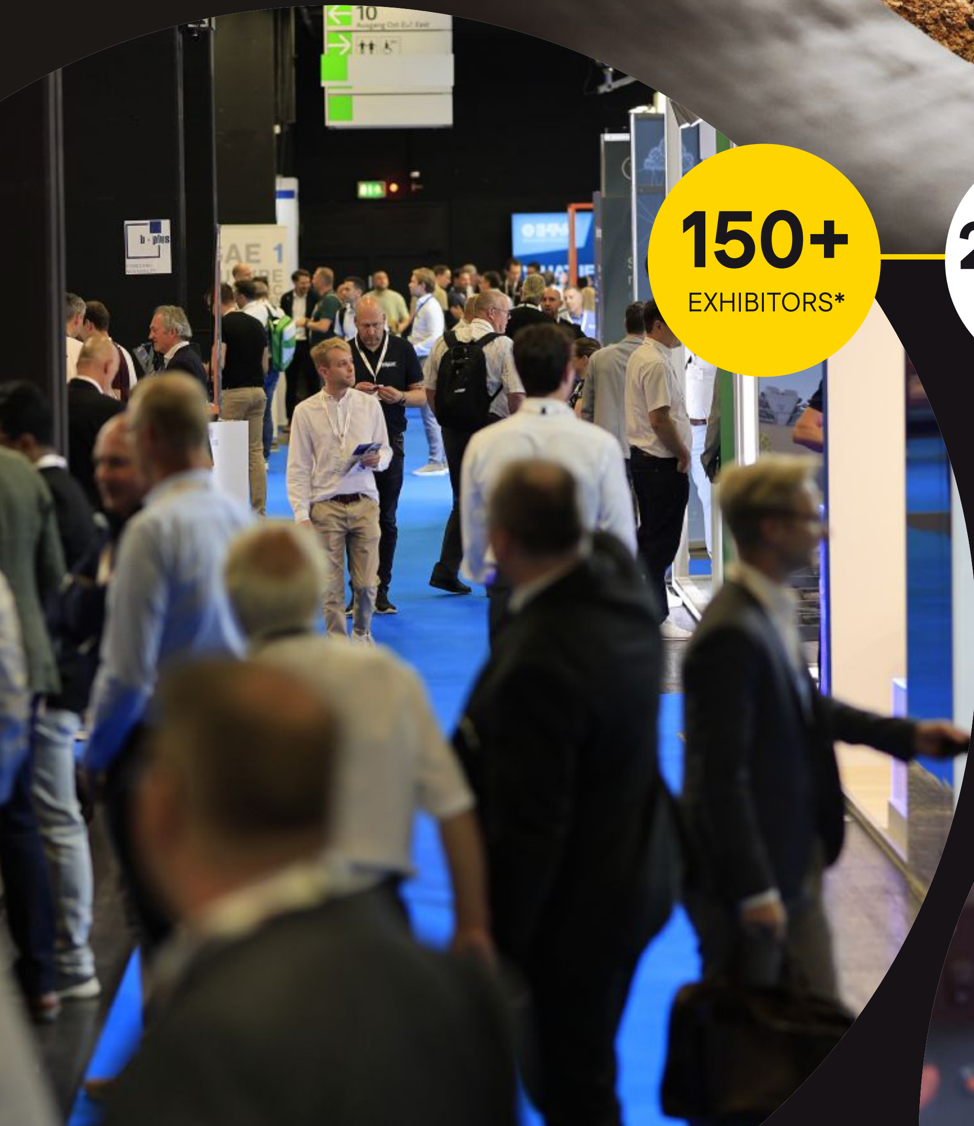

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In association with the National Fluid Power Association (NFPA)

Engineering excellence in automotive powertrains

A comprehensive suite of testing capabilities is vital for advanced EV powertrains

In the rapidly evolving landscape of automotive powertrain technology, Emitech stands out as a leader in innovation and reliability. With a comprehensive suite of services ranging from engineering to testing and metrology, the company supports its clients at every stage of powertrain development, including test bench design and manufacturing.

As the automotive industry shifts toward EVs and hybrids, Emitech has positioned itself at the forefront of this transformation. Its expertise in multiphysics electromechanical analysis ensures that it can meet the complex demands of modern EV powertrains. Whether it's computational fluid dynamics (CFD) or finite element analysis (FEA), the company's advanced simulation capabilities provide invaluable insights into the performance and efficiency of EV components.

Emitech's commitment to excellence is reflected in its state-of-the-art testing facilities, offering a wide range of testing services for electric powertrain components, including e-motors, inverters, batteries, high-voltage harnesses and ECUs. Its hydrogen testing capabilities cover fuel cells, tanks and ECUs, ensuring comprehensive support for alternative fuel technologies.

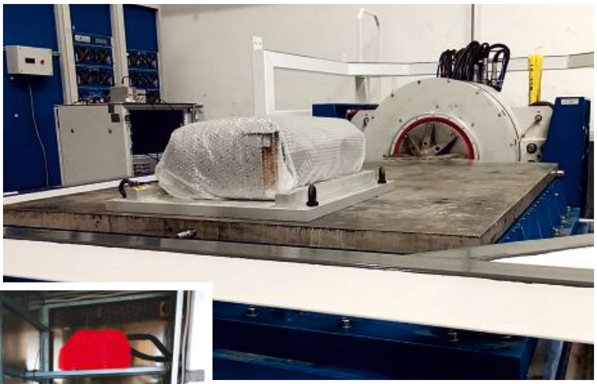
Battery testing is one of the key areas of focus at Emitech, covering a broad spectrum of tests including regulatory and OEM specifications for abuse and fire tests, EMC/EMI tests and climatic and vibration tests. The company can also perform BMS calibration activities and durability testing, and its expertise extends to automotive categories L, M, N and O, as well as the industrial, portable, aerospace and military battery markets.

PARTNERSHIP WITH ALEE

A partnership with Alliance des Laboratoires d'Essai Européenne (ALEE) allows Emitech to offer specialized testing services for R100, R136 and R10 regulations. As a technical service provider via ALEE, the company helps its clients obtain approval for batteries according to R100 standards for various markets (M, N and O). This collaboration ensures that clients' batteries meet the highest regulatory standards.

CLIENTELE AND CAPABILITIES

Emitech's clients include cell manufacturers, pack producers, Tier 1 gigafactories and small-series manufacturers for specific needs such as retrofit, off-road, heavy-duty vehicles and electric bicycles. Thanks to these gigafactory clients, the company has developed extensive expertise in cell and module testing, expanding its testing capabilities to include cycling, characterization, performance, endurance and abuse tests for packs and cells.



Emitech has the capabilities to test a wide range of electric powertrain components

Emitech's testing capabilities accommodate a wide range of device under test (DUT) characteristics, including packs up to 1,000kg, 1,000V, 1,000A. This includes supervising modules without battery management systems (BMS), and monitoring each cell's voltage and temperature, with testing covering cylindrical, prismatic and pouch cells, from 50g to 4kg and 2.5Ah to 200Ah.

REGULATORY COMPLIANCE

Emitech guarantees compliance with regulations such as R100, R136, R10, IEC 62619, IEC 62620 and IEC 62133. This is particularly valuable for the reuse of cell and module subassemblies in stationary and portable applications.

For production runs exceeding 100 batteries, obtaining UN38.3 self-certification is essential. Although UN38.3 is not a formal standard, it is a critical requirement outlined in UNECE's *Manual of Tests and Criteria*, Revision 8 (2023). This certification acts as a logistical passport, facilitating the safe and efficient transportation of batteries.

Since February 18, 2024, CE marking has been mandatory for all batteries under Regulation (EU) 2023/1542. This regulation sets requirements for durability, performance, carbon footprint, recycled content, safety and waste management, introducing extended producer responsibility. Obligations extend beyond 2030 depending on the battery type. Emitech assists manufacturers in determining their obligations and analyzing the regulatory scope applicable, in addition to specific requirements for their initial application field, such as automotive. ⦿

Emitech
To find out more, scan the QR code or visit:
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New sealing materials for EVs and hybrid vehicles

The constantly evolving demands of electrification require fresh developments in sealing technology

The future of the automobile lies in electric mobility, and battery safety has become an absolute priority. Complying with new regulations and ensuring the protection of property and users in the event of fire or gas emissions are major concerns and responsibilities for auto makers and mobility equipment suppliers. In the event of a thermal runaway on a battery pack, users must be evacuated, vehicle operability must be ensured for as long as possible and gas emissions into the environment must be managed.

1. Hutchinson's chemists have developed a halogen-free, fire-resistant EPDM elastomer specifically for EV applications

This extreme case requirement is becoming a guide for eco-design initiatives, and systems must be designed to limit the risks. At Hutchinson Precision Sealing Systems, decentralized product and materials development teams work closely with manufacturers and technical sales teams in contact with customers. They draw on the group's research and innovation resources in scientific computing, digital simulation and physical-chemical knowledge of materials.

Building on these strengths, the company's chemists have developed a halogen-free, fire-resistant EPDM elastomer formulation for electric mobility applications. This compound meets UL 94 V-0 requirements, the most stringent level of the UL standard, and avoids the toxic nuisance of halogenated compounds. Designed for battery pack and cooling circuit seals, this material combines excellent fire resistance, chemical compatibility and mechanical properties for

2

long-lasting sealing, even at low temperatures. As part of the objective of reducing CO_2 emissions, the new refrigerants R744 (CO_2) and R290 (propane), with their lower environmental impact, are changing conditions of use and refrigeration systems. To ensure that they operate at full efficiency and remain well contained, the materials and products need to ensure a perfect seal.

Hutchinson teams have developed a new EPDM compound (PFAS-free) to meet the sealing needs of heat pump components using the refrigerant R744 (CO_2). This refrigerant is of growing interest to auto makers and equipment manufacturers as a response to environmental challenges and vehicle autonomy. R744 is a natural, non-flammable, PFAS-free fluid, with a GWP (global warming potential) of 1, far better than the R1234Y currently in use. Hutchinson's laboratories carried out specific tests on the resistance of materials to explosive decompression to obtain the final formulation, in compliance with the Norsok M-710 standard: Rating 0, confirming the absence of defects after exposure.

3

In addition to its contribution to the energy transition, Hutchinson is committed to a sustainability approach aimed at reducing its Scopes 1 and 2 emissions by 50% by 2030, and achieving carbon neutrality by 2050. The group is working on product lifecycle analysis and eco-design of new products, and has created the resolutions range of sustainable products and the revea range of materials formulated with significant levels of recycled and bio-sourced ingredients. To obtain these labels, products and materials are analyzed according to a rigorous methodology that includes a comparative lifecycle analysis. The criteria put forward are reduction of CO_2 emissions, weight reduction and the use of recycled or bio-sourced materials without competing with food crops.

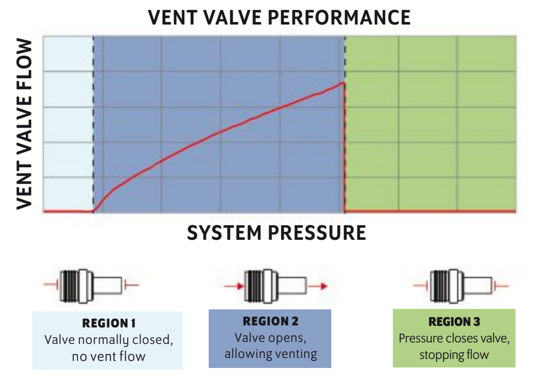
2 & 3. Hutchinson has conducted extensive tests to ensure both the fire resistance and sealing performance of its new material

Specializing in the formulation of materials since 1853, Hutchinson has developed a wide range of elastomer compounds approved by the world's leading auto makers and equipment suppliers. The group is keeping pace with developments in the automotive sector, offering sealing solutions that meet the new challenges of mobility, comply with the latest regulations and take into account the technical, sustainability and economic constraints of the market. ⦿

Hutchinson
To find out more, scan the QR code or visit:
www.hutchinson.com

Precise fluid control for transmission applications

Increasing performance in automotive transmissions is about maximizing efficiency while minimizing footprint



1. The vent valve purges air from the system during startup and prohibits air from being drawn back in while the system is shut down

2. The Lee Company offers innovative fluid control components that help vehicle designers save space and weight in their transmissions

Design engineers are tasked with improving fuel economy by developing more responsive transmissions while reducing the size and weight of corresponding subsystems. Although advances in transmission design have improved system efficiency, demands for better fuel economy and lower emissions mean that older solutions may not meet the design challenges of an evolving – and increasingly electrified – automobile market. Thanks to their innovative designs, The Lee Company's components help auto makers meet the performance and reliability standards required for next-generation transmissions.

DESIGN CHALLENGE: HIGH PRESSURES IN TRADITIONAL TRANSMISSIONS

Historically, vehicle designers have improved efficiency in automatic, continuously variable and dual clutch transmissions by adding gears and gear ratios to amplify torque and boost fuel economy. As design trends evolved, system pressures increased to accommodate the needs of higher-speed transmissions and minimize weight. The Lee Company has developed components specifically for these high-pressure applications. Its pressure-relief valves provide quiet, stable pressure control to protect systems from over-pressurization or pressure spikes. They offer higher flows in a smaller envelope than other traditional valves or in-house ball and spring designs.

Miniature Lee check valves are rated for high pressures to prevent leakage. Designed for durability, they succeed where in-house solutions fail due to intense pressure or poor casting designs.

Lee expansion plugs provide a leak-tight seal without secondary retention methods, delivering repeatable performance even under the highest pressures. Plugs are available in a variety of styles, sizes and materials and are rated for pressures from under vacuum to 483 bar.

DESIGN CHALLENGE: LOW PRESSURES IN ELECTRIC VEHICLE DRIVE UNITS

EVs use electric drive modules, electric drive units or e-axles to distribute torque within the vehicle. These applications require significantly lower average pressures than internal combustion engine transmissions. While design engineers may be tempted to use solutions from cooling systems – which have similar pressure profiles – here, these components may not offer the same precision or performance with oil as they do with water. In addition, traditional cup or freeze plugs pose a significant leakage risk when used as external plugs.

The Lee Company offers components to replace traditional cup or freeze plugs in electric vehicle drive units. These components feature visual indicators to confirm proper installation and do not require the use of adhesives – which add unnecessary cure time and cost, as well as an additional processing step. The Lee Betaplug is a pre-assembled expansion plug designed to seal cross-holes leak-tight without threads, O-rings or sealant. In some cases, in-house cooling jets are made by drilling large holes in cup plugs. These parts may fail to produce adequate or targeted flow to specific areas in the gearbox at lower pressures. Lee targeting orifices allow designers to cool hot spots in gearboxes with more precision, and therefore less coolant, compared with these in-house cooling jets.

DESIGN CHALLENGE: AIR MANAGEMENT IN THE MODERN TRANSMISSION

Air can be a serious issue for any type of hydraulic system – whether within an automatic, dedicated hybrid transmission or an electric vehicle. The Lee Air Bleed Orifice removes trapped air while minimizing hydraulic pressure losses. It contains a small precision flow orifice that is ideal for removing a small amount of air trapped at a high point. Lee vent valves can purge large amounts of trapped air from systems during startup events. This normally closed valve opens to release air as the system is pressurized and closes once the operating pressure is reached. ⦿

The Lee Company
To find out more, scan the QR code or visit:
www.theleeco.com

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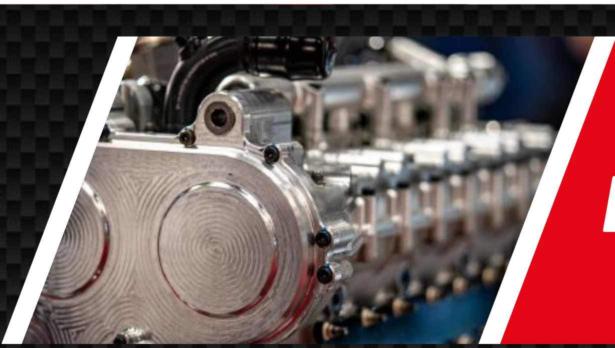

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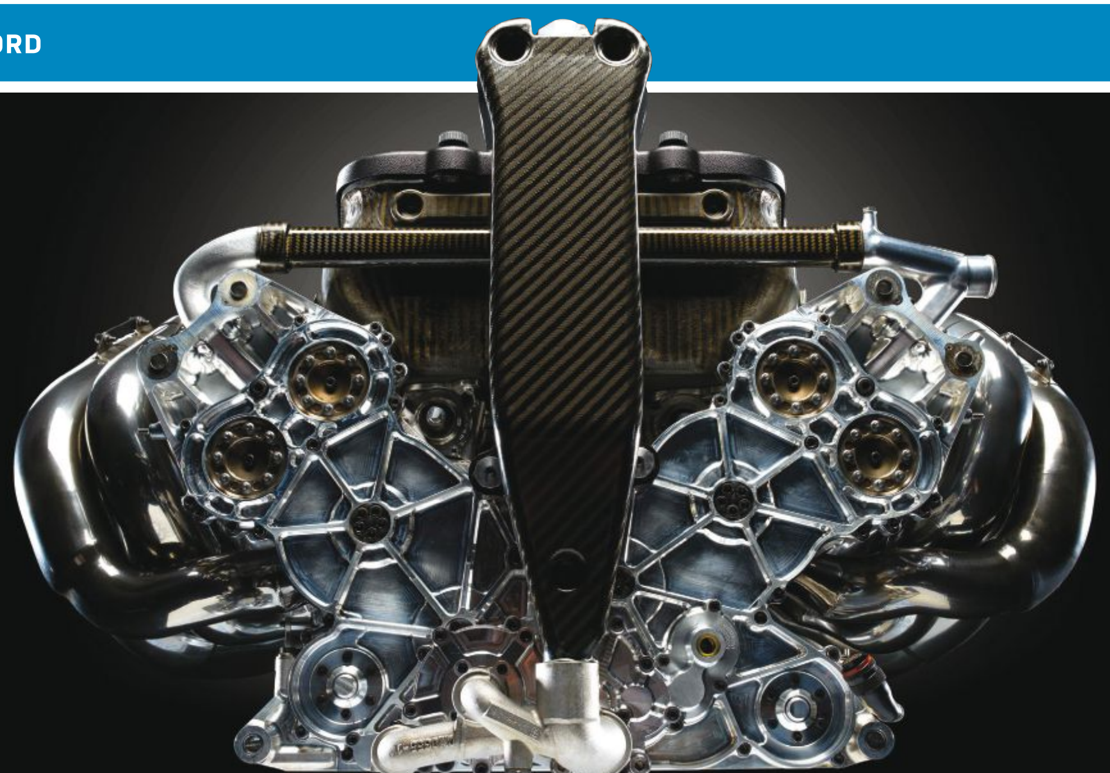

The 20,000rpm V8

COSWORTH'S CA WAS THE PINNACLE OF HIGH-RPM FORMULA 1 ENGINES

Words: Lawrence Butcher

There has been a glut of 10,000rpm-plus road-car engines of late, catering to demand from well-heeled driving enthusiasts for aural thrills from their hypercars. The Cosworth V12s for Gordon Murray Design and Aston Martin spring to mind, and of course Bugatti's V16, also of the same parish. Lamborghini's L411 V8, detailed on page 4, is probably the most accessible, coming in at just under US$235,000, compared with the multiple millions for a GMA or Bugatti.

It is an impressive feat indeed to field a fully emission-compliant road engine that can hit over 10,000rpm. However, in the world of racing, before rule-makers and penny-pinchers had their way, 20,000rpm was on its way to being the norm.

In the early noughties, an RPM battle was underway in motorsport's top class. With the 3.0-liter V10 era in full swing, BMW was the first to hit 19,000rpm. Rule changes for 2006 – switching to 2.4-liter V8s – saw a brief period of even dizzier heights, led by the Cosworth CA, which – before regulations spoiled the party – could top 20,000rpm in race trim (and even run for 800km+ before a rebuild was needed).

That the CA could reach such stratospheric heights was not the work of a moment. It was the culmination of an evolutionary journey that began with Cosworth's original F1 V8 – the DFV – which burst onto the scene in 1967. Those first DFVs made around 400bhp at 9,000rpm from a 3.0-liter capacity. The CA made just shy of 800bhp from 2.5 liters, and weighed in at 95kg rather than the near 170kg of the DFV. That said, the basic architectures of the two engines have much in common.

Key to the CA's ability to rev was an unwavering attention to detail in the fight against friction and reciprocating masses, particularly in the piston. In the case of the CA, its 98mm pistons ran in coated bores – Cosworth started using linerless blocks in 1999 – and, impressively, were produced from (relatively) conventional aluminum alloy because aluminum beryllium and metal matrix composites had been outlawed by this point. Thanks to the 98mm bore and tiny 39.77mm stroke, piston speeds of 26.4m/s at 20,000rpm were high but not unreasonable.

However, to reliably use aluminum alloy for the piston, Cosworth needed to be on top of its materials analysis game; for example, refining its FEA processes to take into account the effect of elevated temperatures on the piston material.

Helpfully, it had a vast historical archive of data from other, similar engines to correlate against. The result is a piston that, when compared with its DFV forebear, is spectacularly complex in its form, with reinforcement added exactly where needed and material removed where it is not.

Of course, there was far more to the CA than just its pistons, such as the tiny-stemmed (5mm) titanium inlet valves and 6mm-stemmed, sodium-filled exhaust valve, and the jewel-like crankshaft, produced from triple vacuum arc remelted steel, nitrided and then super-finished (Cosworth did experiment with a welded hollow crank, and also the use of roller bearings).

Sadly, the CA only got a single season to sing its 20K symphony. In the constant dance around escalating costs, 2007 saw maximum revs in F1 capped at 19,000, before being dropped again to 18,000 in 2009.

Of course, the current 1,600cc V6s, while technical marvels in their own right, come nowhere near such figures. Though there is a nominal regulation limit of 15,000rpm, manufacturers have found a friction/efficiency sweet spot of around 12,500rpm.

In some ways, it is ironic that the current F1 rules were introduced to promote a production car link (and their efficiency is unquestionable). Yet when it comes to aural entertainment, it is RPM that is once again providing the hook for those at the ultra-high-performance end of the road-car spectrum. ⦿

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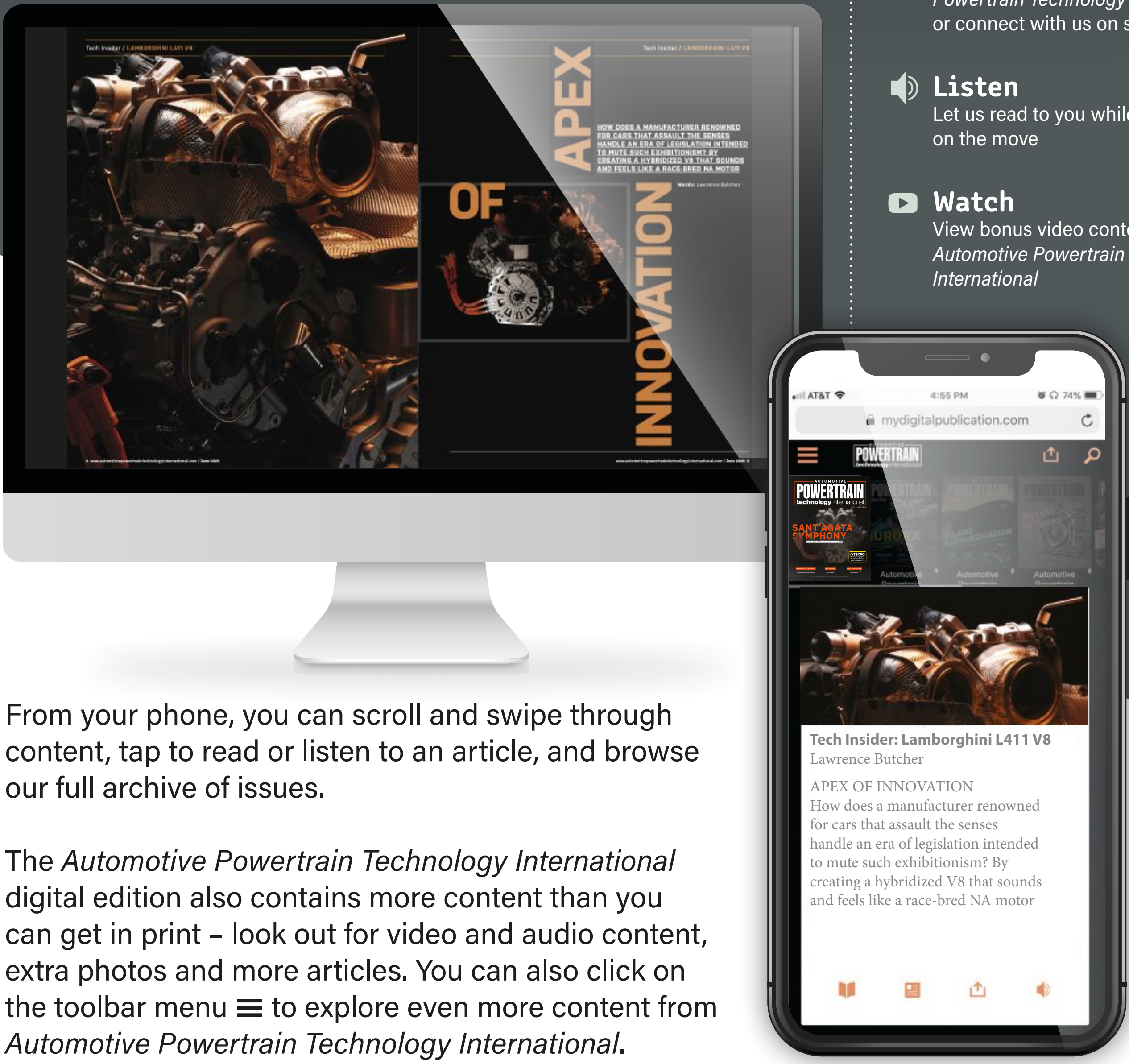

Tech Insider: Lamborghini L411 V8
Lawrence Butcher

APEX OF INNOVATION
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